1962

Study of the copper-uranium deposits at Vilcabamba, Department of Cuzco, Peru

Oscar Aguilar

STUDY OF THE COPPER-URANIUM DEPOSITS AT VILCABAMBA, DEPARTMENT OF CUZCO, PERU

BY

OSCAR AGUILAR M.

A

THESIS

submitted to the faculty of the

UNIVERSITY OF MISSOURI SCHOOL OF MINES AND METALLURGY

in partial fulfillment of the work required for the

Degree of

MASTER OF SCIENCE, GEOLOGY MAJOR

Rolla, Missouri

1962

approved by

J C Armstrong, advisor A. Legsdin

Paul Dean Proctor Carl R. Christiansen

CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF PLATES

ABSTRACT

Uranium has been known in the Vilcabamba district of Cuzco, Peru since 1954. Copper ores of high silver content were worked by the Spaniards during the seventeenth andthe early eighteenth conturies. At the beginning of the twentieth century these ores were worked intermittently; during the last fifty years nomining operation has been going on.

The oldest rocks in the thesis area consist of Ordovician phyllites. The presence of Devonian in the area is questionable, but has been recognized 5 km. away from the thesis area. A conglomerate of limited lateral extent of Mississippian age overlies the Devonian (?) or Ordovician formation. Middle (?) and Upper Pennsylvanian and Lower Permian rocks are represented by about 2000 m. of Tarma and Copacabana limestone. Igneous rocks of Middle (?) Permian age appear to overlie the limestone formation. This is called the Mitu group and consists, in addition to the igneous rocks, of coarse red clastics overlying unconformably the Copacabana group. In the limestone area, two main dikes of grachyandesite composition appear to intersect the formation.

Copper-nickel-uranium minerals of probable hydrothermal and contact mesosomatic origin occur as lenses or fissure fillings in the Permocaraboniferous limestone some associated with skarn.

The ore minerals are tetrahedrite, bornite, chalcopyrite, covellite, niccolite, pitchblende, molybdenite and a variety of sulforarsenides of nickel and cobalt. Gangue is predominantly calcite and dolomite, with quartz in minor amounts. Skarn minerals are garnet epidote, apatite, hematite, and magnetite.

The major amount of ore minerals seems to be structurally controlled, but chemical-physical conditions of the host rock may also play important roles.

An economic evaluation can not be made at the present stage of exploration. More drilling and mapping is needed. Other factors which will affect this evaluation are the high cost of transportation and difficulty in evaluating tonnage due to the irregular distribution of the ore zones.

I. INTRODUCTION

A. LOCATION AND ACCESSIBILITY

The thesis area is a part of southern Peru, located at about 13°06' south latitude and 73°03' west longitude. According to RAIMONDI (1902) it is located in the central Cordillera, and BOWMAN (1916) calls this area Cordillera of Vilcapampa (compare Figure 2). As shown in various figures (2, 3, etc.) the area has a rugged relief. It is located in the province of LaConvencion, department of Cuzco.

The nearest village is Vilcabamba. It is located in an open valley entirely surrounded by hills, rising like the sides of an amphitheater to altitudes of several hundred meters above this town. This central valley is about 1.5 km. long from southeast to northwest and 1 km. wide.

As Vilcabamba is located at an elevation of 3500 m. above sea level, the temperature of the region is rather cool. The entire aspect of the region about the Vilcabamba mining district is desolate, since much of the time the sky is covered with heavy clouds from the tropical Amazon basin. The trails are rough, and the hills stand out bare and abrupt on all sides. The timberline is at about 2800 m. The lower slopes of the hills are covered with short green

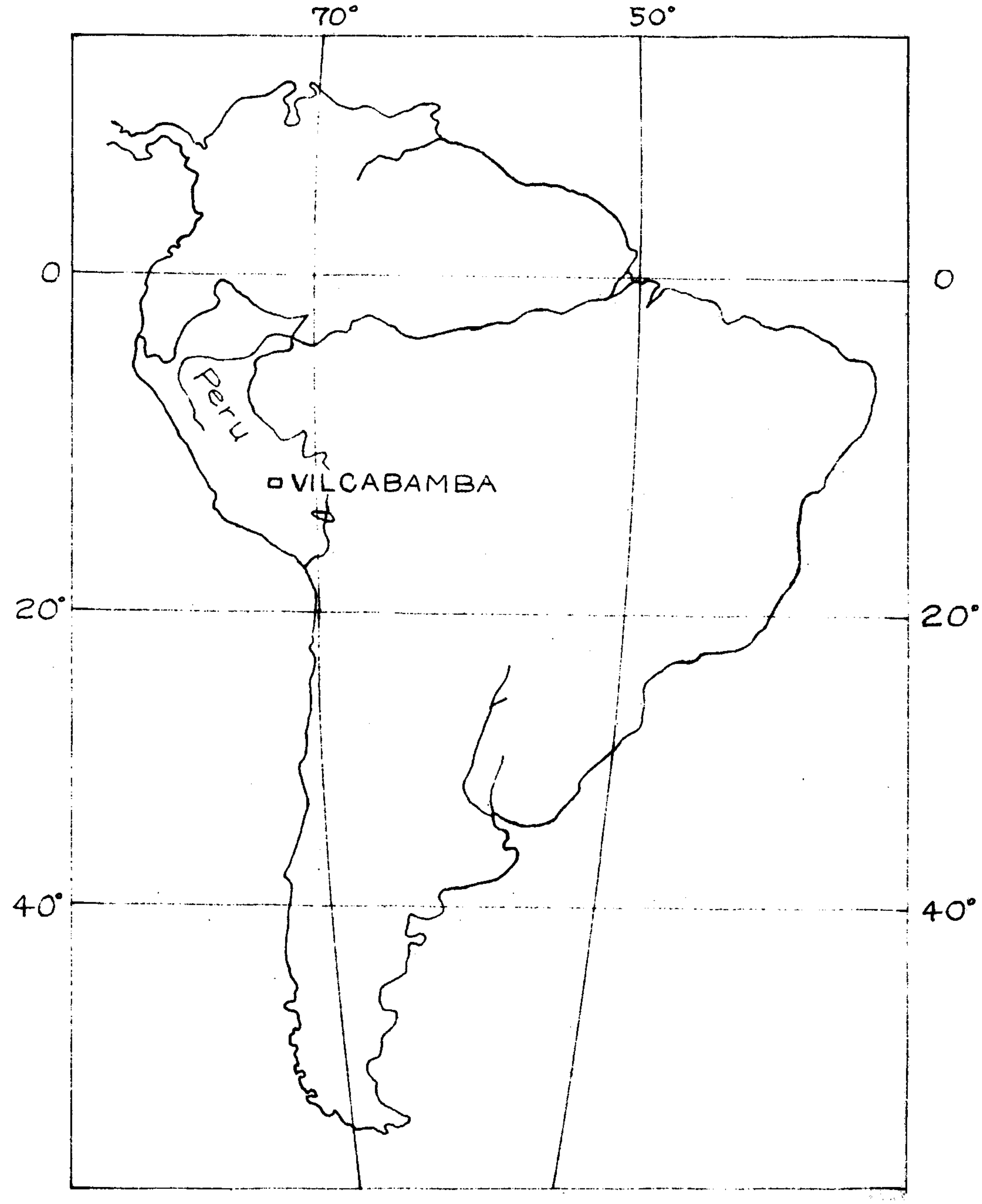


Figure 1 The Location of the Thesis Area in Regard to Peru and South America

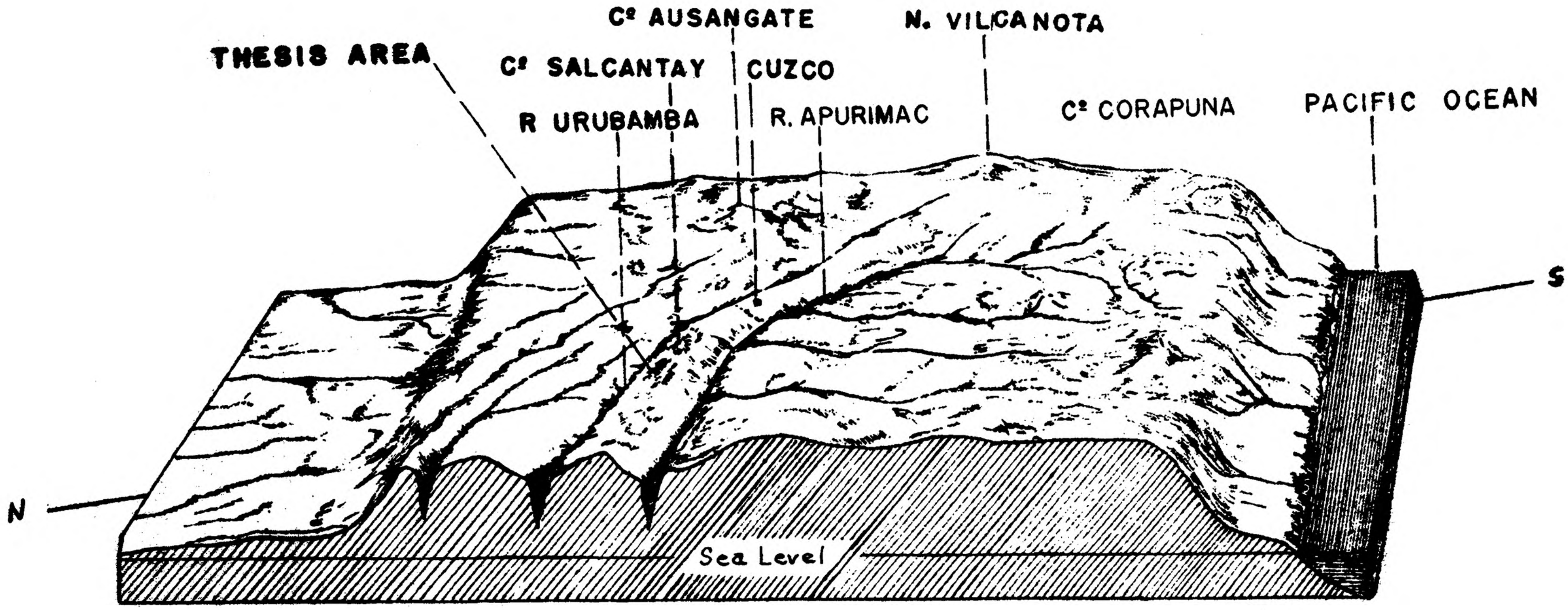


Figure 2 Oblique View of a Portion of the South Peruvian Andes

grass and a variety of star-leafed moss. No trees or plants except barley and potatoes can be grown; for other vegetables and grain the climate is too cold or the altitude too great.

The country is almost uninhabited except for villages along the Vilcabamba River and a few shepherd huts on the mountain sides. Cuzco, the closest city, can be reached in two ways from Lima, the capital of the country. First by travelling south by airplane from Lima to Cuzco. This trip of roughly 400 km. can be made in two and a half hours. Cuzco can also be reached by road over various passes. The trip of 1100 km. is made in approximately 30 hours over roads most of which are in poor condition. From Cuzco a narrow gage railroad leads down the Urubamba Valley to Santa Teresa in three hours, covering a total distance of about 100 km. From here, Chaullay is reached by car travelling northward over a narrow gravel road.

From Chaullay the trail to Vilcabamba village enters the valley of Vilcabamba, and follows along its stream to its source area in the bogs of the upper Crodillera to elevations of about 4200 m.

From Chaullay and Tarqui (about 1000 m. and 2500 m. elevation respectively) over a distance of about 50 km. the trail leads through luxuriant tropical growth. From 2500 m. to 3700 m. potatoes still can be grown, as well as some garden plants, and barley and corn. As stated above, the timberline occurs at an elevation of 2800 m. Although grass grows up to 4500 m., agriculture ceases at 3800 m. From Pucyura the ascent becomes steeper, the air gets chilly, and high peaks become visible, some of them with permanent snow and ice.

The Vilcabamba village can be viewed from the actual mineral area. It is located at the end of a U-shaped canyon along which a swift stream winds its way through a tangle of shrubs. This village has about 30 thatched stone and mud-walled houses and approximately 60 people.

For more than eight centuries this well-worn trail has been the passage of "llamas*". In earlier times, and later also of horses and mules and patient Quechua carriers taking material of trade to and from Cuzco. Along the route are some small towns such as Lucma, Pucyura, Huancacally. They are larger than Vilcabamba and also built of thatched adobe (unburned earth brick) or stone-huts, the homes of the Andean shepherds.

---

*"Any of several wild and domesticated South American ruminants allied to the camels, but smaller and without a hump;.... used as a beast of burden in the Andes." (WEBSTER's New Collegiate Dictionary)

Because of the high altitude of the Andes, excursions have to be planned with due consideration as to the constitution and health of the individual. Perfect freedom from heart, pulmonary, or circulatory weaknesses is essential to a prolonged stay in the rarified atmosphere.

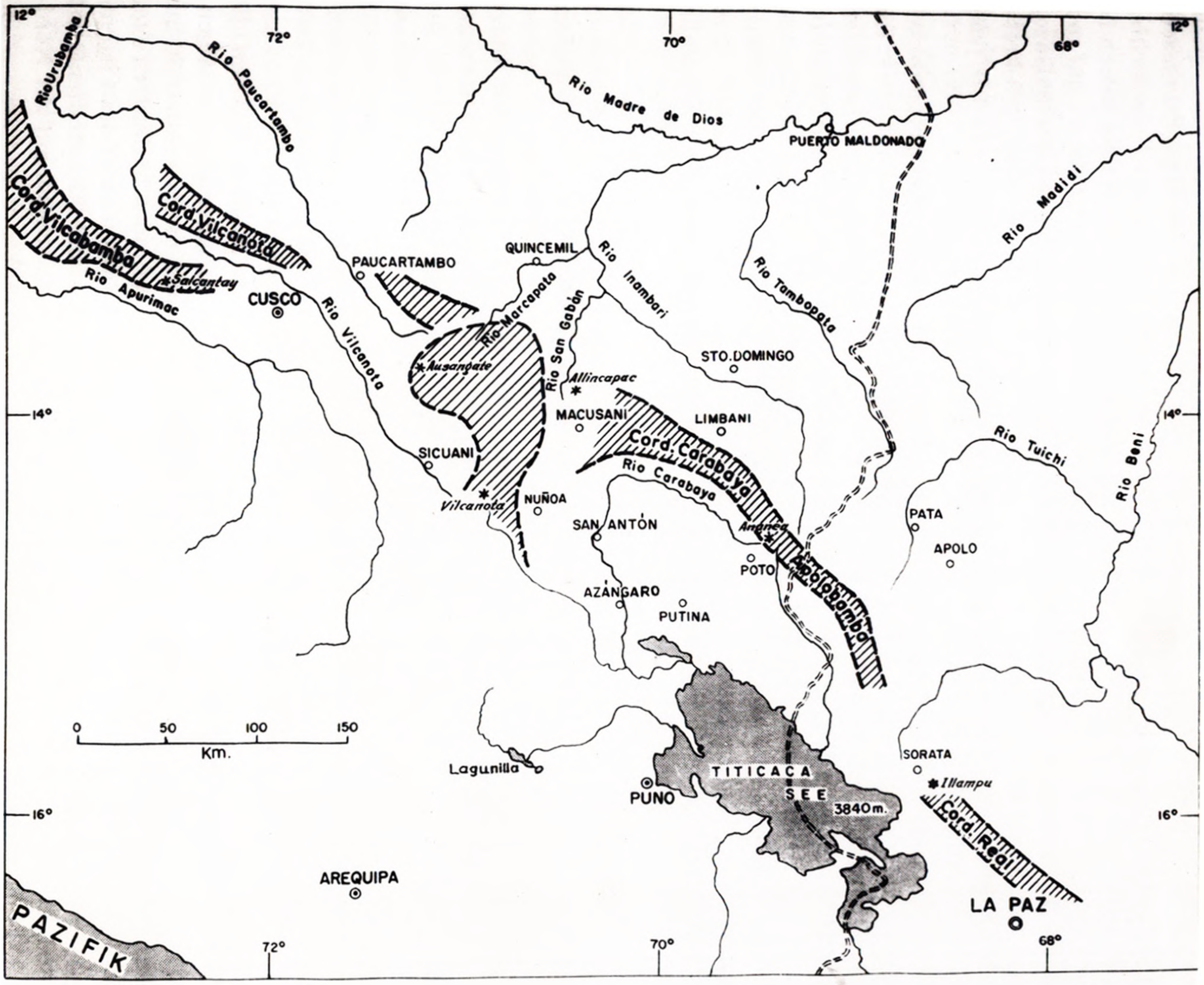


Fig. 1. Übersichtskarte mit Gewässernetz und orographischer Gliederung der Ostanden zwischen Südperu und Bolivien (= = = = Landesgrenze).

Figure 3. Location of the Cordillera at Vilcabamba, in Southern Peru (from KATZ, 1959).

B. SHAPE AND SIZE OF THE AREA

The shape of the area studied for this thesis is nearly rectangular as seen in Figure 10 and is 3 km. long and 1 km. wide. The northernmost point is the gorge of Calderon, which trends roughly E-W. The northern portion comprising the areas covered mostly by volcanis were not studied in as much detail as the southern portion. The area is limited in the south by a line trending E-W, which passes nearly through the "Pacopata" camp, the base camp of the exploration project later described. The most westerly boundary is the Cerro Yunguiyoc, which is a well defined crest line trending roughly N-S. Its western flank abruptly descends to great depth while the eastern flank consists of a dip slope. The eastern side is bounded by the Huamanapi glacial valley which trends north.

The area reported here is 3 km. long and 1 km. wide. Both geological and radiometric maps were prepared on a 1:200 scale. They are included as an Appendix, reduced to 1:20,000.

It may be noted here in passing that at Puntarayoc 6 km. E of the thesis area similar geologic and radiometric maps were made. Both show the same pattern of mineralization as here reported.

C. CULTURE

The approximately 60 inhabitants of Vilcabamba understand very little Spanish and a bilingual guide is of great help. They live in stone and adobe huts, but most of the buildings are either abandoned or only temporarily used. The population is largely confined to grazing small herds of sheep or horses and on a small scale to agriculture purposes. The land is practically valueless since it is too steep and rocky for farming.

Food is scarce and almost unobtainable, and it is advisable to take a plentiful supply of provisions on any journey to this area. Water supply is also scarce; however, 1 km. away water is sufficient for domestic use, and 4 km. beyond this near Huancacalle, there is enough water to develop electric power and for concentration plants.

The closest road access to the area is at Chaullay which lies 80 km. to the east. Transportation and travel to the area is made in 3 days on horseback over a fair trail, which follows the Vilcabamba stream, as mentioned above.

The nearest police station is at Pucyura which is about 7 km. from Vilcabamba. Medical facilities can be found at Quillabamba, about 100 km. distance from Vilcabamba.

D. PURPOSE OF INVESTIGATION

The purpose of the original work was to supply basic geological data to the Junta de Control Energia Átomica of Peru, engaged in a uranium prospecting program, and to add to the geologic knowledge of an area where only scanty geologic work had been done previously. Particular attention was devoted to the economic possibility, significance, distribution both horizontally and vertically, and the natural environment of the mineral deposits of the area.

Emphasis was placed on the role played by ore solutions under various temperatures, pressures, influences of the host rocks, and their relation to structures in controlling the forms of the deposits. Geological principles were applied in order to recommend the exploration of new areas.

No attempt has been made to describe each individual prospect pit except as it illustrates specific characteristics of the deposits. Exploration has not been sufficient or adequate in all cases to provide data for the formulation of more accurate ideas on the mineralization and characteristics in depth. More time for greater detailed geologic exploration is needed. Nevertheless, the work is a contribution to the geological knowledge of the Vilcabamba uranium prospect in Peru. While the overall work is the result of a group of geologists of the Junta de Control de Energia Atomica, the author directed the planning and the first phases of physical exploration. Materials for the thesis was gathered at this time.

The problem consists of the description of the geologic setting of the Vilcabamba uranium prospects, a laboratory investigation of the ores, in particular the study of the mineralogic composition and the mineral associations, as also of the chemical and mineralogic composition of the igneous rocks of the area.

E. ACKNOWLEDGMENTS

The author wishes to express his grateful appreciation to the General Jorge Sarmiento C., President of the "Junta Control de Energia Atomica" of Peru, and all the members of the Directory for the economic support during the period of his study at the Missouri School of Mines and Metallurgy.

The author takes this opportunity to express sincere appreciation to Dr. G. C. Amstutz, Professor of Geology and advisor of the writer's graduate study; his aid, guidance and suggestions were of great value in the accomplishment of this thesis.

Thanks are given to Dr. Paul Dean Proctor, Chairman of the Geology Department for the research-grant-in-aid from the McNutt Memorial Foundation, and also for his permanent and friendly suggestions in all aspects during the author's stay at the School of Mines and Metallurgy.

Cordial thanks are also extended to all other staff members of the Geology Department, from whom the writer has received valuable instruction and guidance.

Thanks are also due to my friends Erwin Mantei and Mike Greely, colleagues in this school for their unselfish and frequent assistance in many respects. Thanks are also extended to may friend Ing. Juan Sosa from Peru for his interest in collecting a part of the author's rock samples.

Finally, thanks are given to all persons and friends who have in any way contributed to the completion of this thesis.

F. METHOD OF INVESTIGATION

Geological investigations in Peru with respect to radioactivity minerals is recent. On the basis of earlier reconnaissance exploration, the J.C.E.A. of Peru initiated in 1958 a search for uranium minerals in the Vilcabamba area.

The writer began field work in August-September, 1957. Detailed geologic maps and a radiometric survey on the part of the Huamanapi and Calderon areas were prepared over areas which seemed most likely to contain uranium mineralization. Systematic surveys of every part of the zone where the existence of uranium was expected has been in progress from 1957 to 1960.

The surface geology of the Vilcabamba area was mapped on a scale of 1:200 m. during May to July, 1958. Mineralogic features (mineralization, alteration, and lithology), and structural features (faults, fractures, etc.) were the basis of the exploration program. As a result of this work, three diamond drill holes were drilled in 1959 to determine possible ore mineralization at depth. To date (1960) five diamond drill holes have been completed.

1. Mineralogic Guides

The color of the limonite as an alteration product of the pyrite was recognized easily in the field; but in a few cases other yellowish or green secondary stains were also observed. All occurrences of mineralization were recorded, while old prospects and abandoned mines were searched and mapped. Few, if any, of the alteration criteria associated with uranium deposits differ appreciably from those of copper - lead - zinc and other metals.

The lithologic guide was, all over the area, the Permo-carboniferous Copacabana unit. Inside the thesis area proper not a single trace of mineralization was encountered outside this stratigraphic unit.

2. Structural Guides

Breccias, faults, and fractures were principle guides in prospecting. In the Huamanapi zone (Esperanza prospect) calcareous breccia contained some spotty chalcopyrite mineralization with minor uranium. In both the Calderon and Huamanapi zones fractures were useful guides.

Other possible controls were considered and the view held that other unsuspected areas and conditions could also contain uranium. The main guides soon appeared, however, to be structural and mineralogic features.

3. <u>The Technique of Prospecting</u>

Prospecting was carried out basically in two stages:

a. Reconnaissance survey

b. Detailed survey

a. <u>Reconnaissance</u> surveys were made by one or two geologists and two workers, usually on horseback or on foot. These designated some localities which demanded priority in the field operations. This priority was based on indications of radioactive anomalies combined with litho-ligical, mineralogic and structural criteria.

b. <u>Detailed</u> survey consisted of detailed geological mapping (1:200) and radiometric readings measured two meters apart. Minor excavations were made at the most radio-active areas, and uranium samples of the richest pod or lens-like outcrops were collected. The purpose of detailed geologic and radiometric prospecting was to define the geometry of the mineralization.

4. <u>Principles Applicable</u>

The radioactive gama emission of the uranium along with Th, Rb, Hf, K, offers a unique means of direct qualitative detection of their significant concentrations. The radiation detector is nearly always a Geiger counter or a scintillation counter, each of which produces electrical impulses of a rate dependent upon the radiation intensity. Both of these instruments measure the ganma radiation from near-surface, but in somewhat different ways. F. W. STEAD (1956, p. 714) states:

> "Using sensitive radiation detectors, uranium prospectors need not be able to identify radioactive minerals not to have more than a cursory knowledge of geology; a marked increase in radioactivity indicates where further work should be done."

In another paragraph he states,

> "Unfortunately, even the most penetrating gamma radiation from radioactive materials is effectively absorbed by a few inches of intervening materials."

5. Instruments

In the prospecting for radioactive minerals, Geiger counters or scintillometers are virtually indispensable. This is mainly because the uranium minerals are usually dispersed rather than massive; therefore it is often difficult to recognize them by the naked eye only. Secondary minerals, which aid in visual detection, are commonly washed away or dissolved from directly exposed rock surfaces. In the case of Vilcabamba they are subject to strong erosion due to the sharp topography and a great amount of precipitation.

DAVIDSON and BOWIE (1956, p. 659) describe a Geiger-Muller Counter and the scintillometer as follows.

> "In the former (Geiger Counter) the ionizing radiation produces secondary electrons which are amplified by gas multiplication within the envelope of a Geiger-Muller tube, where as in the latter (scintillometers) the radiations produce scintillation in a phosphor and these are amplified with the aid of a photomultiplier (or electron multiplier) tube. Less than one percent of the gamma rays passing through the Geiger-Muller tube produce a secondary electron which will be counted, but nearly all the rays entering a large thallium - activated sodium iodide crystal will cause scintillations capable to be recorded."

In another paragraph he continues:

> "An efficient scintillometer is about 50 times more sensitive to terrestrial gamma rays than a Geiger-Muller Counter, and as the two instruments respond similarly to cosmic rays it may be expected that it is 50 times easier to detect an anomaly with a scintillometer than with a Geiger counter. This, unfortunately, is not so, since the background gamma count is also increased substantially with a scintillometer."

PEIRSON and FRANKLIN have indicated that the performance factor, or the ability to detect a radioactivity anomaly can be as much as seven times higher in a scintillometer than in a Geiger-Muller counter if the two detectors are of the same volume. But since it is very much easier to make large Geiger_Muller tubes than it is to make large efficient volumes of scintillation material, this factor is in the practice reduced to about three.

WILSON (1954) and DAVIS (1954) point out, "The portable scintillation counter has several advantages over the Geiger-Muller counter:

(1) higher efficiency for gamma-ray detection,
(2) lower relative cosmic-ray background because of the higher gamma-ray efficiency; and
(3) relative short resolving time, allowing higher counting rates without serious coincidence loss.

Comparative disadvantages of the scintillation counter are:

(1) present high cost and scarcity of large thallium-activated sodium iodide crystals.
(2) small pulse output from the photomultiplier requiring a better amplifier circuit than for the Geiger-Muller Counter tube; and
(3) high voltage regulation for the photomultiplier is far more critical than regulation for Geiger-Muller counter tube."

Figure 4. Geologists at work during the reconnaissance survey in Negrillas area. The scintillometer is the more efficient tool for radioactive detection.

G. PREVIOUS REGIONAL WORK AND HISTORY OF LOCAL INVESTIGATION

1. Previous Regional Work

D'ORBIGNY (1842) was the first to attempt a systematic investigation in the area of Cuzco adjacent to the area which is the object of this study. It is not the writer's intention to review all the history connected with this matter, but the more outstanding papers dealing with the stúdy of the thesis area will be briefly discussed. The next important step in the study of the general geology was accomplished by FORBES (1861). RAIMONDI (1862) who contributed various observations partly of a paleontologic character, showing Carboniferous outdrops at an elevation of 400 m. above the Apurimac Canyon, at a locality intermediate between the Pichis River and Cuzco. According to NEWELL (1953), TOULA in 1869, and GABB in 1877, identified a single species from Titicaca as Fusuline Cylindrica Fisher, that is a guide fossils to the Muscovian (Middle Pennsylvanian) of Europe, whereas NEWELL demonstrated later an early Permian age.

A sketch of the geology of South America was read by STEINMANN before the Geological Society of America in 1891. The following information from STEINMANN may be mentioned.

In Devonian times, as is indicated by the sediments, there was an extensive sea embracing the larger part of South America, mainly Brazil and Bolivia (and extending also to Peru). Carboniferous sediments were more restricted, but are known from Peru, Bolivia, and Brazil.

During the Permian, Triassic, and Jurassic, the greater part of the South American continent was above sea level, although, however, Triassic and Jurassic sediments have been found on the western part of the continent.

BALTA (1899) reviewed the Carboniferous of Peru and published a sketch map showing two areas in which the Carboniferous had been shown to exist. According to BOWMAN (1916), STEINMANN (1914), DOUGLAS (1914) and KOZLOWSKI (1914), GERTH (1915) noted "large fusulinas" on the rio Pampas between Abancay and Ayacucho, and slender fusulinas in the limestone of Cerro Ampay at Abancay. In 1919 BERRY and SINGEWALD made small collections of fusulinas from Yumpupata and Chulpampa, Bolivia. LISSON and BOIT (1942) found fusilinas at San Rafael mines while THOMPSON (1943) identified a lower Permian fusulina from deep drill holes in the Ganzo Azul oil field. NEWELL (1949 and 1953), have furnished considerable information on the specific composition of the invertebrate fauna, HEIM (1947), and KALAFATOVICH collected fusulina near Hacienda Tio near San Salvador, on the Urubamba River, 11 miles northeast of Cuzco. R. E. KING was the first to recognize the Permian age of the Upper Carboniferous strata of the central Andes. Finally U. PETERSEN (1958) in two of his interesting papers deals with the generalized geology and stratigraphy and with the intrusions and mineralization of all of Peru.

It seems pertinent to remark, that the more significant contribution to the geology of the region was made by BOWMAN (1916) for the great sections of Upper Paleozoic rocks in south-central Peru. In addition the papers by NEWELL (1949) and NEWELL, CHRONIC, and ROBERTS (1953) were consulted most frequently.

2. <u>History of Local Investigation</u>

The district in which the present thesis area is located, is one of the oldest mining districts of Peru. Mining has been active for many years in a more or less discontinuous manner and on a small scale. The earlier mining operations were focused on silver ores as their primary objective, and most probably they were known and worked by the Incas.

The first serious attempt to develop the mineral resources in the area of Vilcabamba seems to have been made by the Spaniards during the colonial period when transportation costs and wages were not a serious problem. Numerous bodies of rich silver ores were mined and it is likely that much of the ore was mined out in this period and that it was a period of more active mining. The reason why the Spaniards abandoned this zone is unknown.

Since that time various evaluations of the properties in the area have been made for copper, silver, lead, nickel-cobalt and uranium. But the difficult frontier conditions and the extremely costly transportation were always factors which slowed down exploration.

Our first technical knowledge of copper mining in Vilcabamba district dates back to the year 1865 when RAIMONDI visited this district and described not only the occurrence of sulfurarsenides which were used by the inhabitants to poison the bats, but also emphasized the high silver content in the "pacos".

A renewed attempt to develop the deposits were ing made unsuccessfully in 1890 by Martin Pio Concha and Mario Velarde. In 1891 the claim corresponding to this mine was purchased by D. Thomas Polo de la Borda. In 1904 Jose Larrea Rueda supervised the mining area and special attention was given to develop nickel ore.

Small silver production was made by Pablo Bottger (1906) who is reported to have extracted 80 kg. of silver in the concentrates; but was unable to interest anyone in them. In the succeeding years only sporadic prospecting was done. In 1954 Juan Mariana Velasco, a Cuzco lawyer announced he had discovered uranium in the area. In the same year K. Rogger of the U.S. Atomic Energy Commission verified the occurrence of uranium.

About 1956 Juan Mariano Velasco interested Cerro de Pasco Corporation, which took a part of the property under option. Exploratory diamond drill holes gave discouraging results.

Under the stimulus of the high price of uranium, the Atomic Energy Commission of Peru in 1957 renewed the attempt to prospect for radioactive minerals. They located new uranium occurrences in unexplored areas. These are presently being investigated and constitute the subject of the present thesis.

II. GEOGRAPHY

A. THE CORDILLERA OF THE ANDES

The term Andes is used as a general term for the whole mountain system in Peru, and its various branches are spoken of as Cordilleras. The branch to the east of Lake Titicaca is called the Cordillera Oriental and the one to the west the Cordillera Occidental. The joining of these branches to the north of Lake Titicaca is called the knot of Vilcanota, a name taken from a snow-capped peak. From this knot northward three branches are commonly recognized instead of two; the Cordillera Occidental runs parallel to the shore line and rises steeply above the western side of the inter-Cordillera plateaus. These mountains attain elevations of 5000 to 6000 m. above the sea level. The Cordillera Central separates the valleys of Apurimac and Vilcanota. Between these valleys lies the Vilcabamba mining district, while the Cordillera Oriental adjoins the forest region of the Amazon jungle.

The Central Cordillera taken as a whole from the Knot of Vilcanota or nearby it, has a general westerly trend, but consists of many individual mountain ranges with less elevation than the mountain itself (see Figure 3).

According to NEWELL (1949, p. 90) six orogenic cycles are inferred from the stratigraphic record. They are as follows:

1. Orogeny near the "Close" of the Paleozoic (Appalachian orogeny?), followed by peneplanation.

2. Orogency near the end of the Jurassic (Nevadian orogeny), followed by peneplanation.

3. Warping in Cordillera Oriental near the end of the Medial Cretaceous.

4. Folding near the close of the Cretaceous (Laramide?) in Western Cordillera and Antiplano, which may have continued into Puno time.

5. Folding and peneplanation at the close of Puno time (Miocene?).

6. Deposition of Tocaza volcanics, followed by compression from northeast and southwest, to form several overthrust faults (Pliocene?).

7. Peneplanation, forming a surface which merges in Bolivia with post-Puno surface to form regional Puno peneplain.

8. Block faulting and subsidence of Antiplano; origin of Lake Ballivian (latest Pliocene - early Pleistocene).

9. Partial drainage of Bolivian to form Lake Titicaca (Pleistocene - Recent), subsidence of Lake floor

to present depth, simultaneous with late stage of uparching of Andean system. Extrusion of Sillapaca volcanics (Pliocene?, Pleistocene - Recent).

Topographic Setting. The geographic position of the Vilcabamba area is shown in Figure 2. The relief sketch of Southern Peru in the Cuzco area shows the presence of an extensively disected upland region bounded on the southwest by the Peruvian coastal plain and on the northeast by slopes leading to the Amazon Area. This surface which H. E. GREGORY calls the Peruvian Plateau is part of the Andean Plateau on the greatest of the world's highlands. Above this plateau surface, which has an elevation of 4000 to 4500 m. above sea level, rise snowclad peaks. Deep canyons are cut into the surface and lead away from it.

The area pictured stands at an average elevation of about 4000 m. and is surmounted by peaks reaching upward as high as 5500 to 6000 m. The extremes of elevation in the zone are: the summit of the snow-capped peaks of "El Salcantay" (6.200 m.), "El Huayonay", "El Sacsarayoc", "El Kaico", "El Comballa", and, nearby Vilcabamba village, "El Cerro Yunguiyoc" (4710 m.).

In fact, so deeply trenched are the highlands and so narrow the spacing between the gigantic gorges and huge erosion remnants that it is difficult for one standing in the middle of these features to gain a broad view of the whole region. The snow-clad peaks mentioned are gigantic examples of erosion remnants formed by resistant rocks eroded on both sides of the Cordillera Vilcabamba slopes.

The Vilcabamba mountain range probably results from the elevation and greater or less dissection of a more ancient mountain system which had been previously eroded. The elevation of the mountain region was accomplished by moderate deformation in part with strong block faulting.

The temperature of the mining district and hence the effectiveness of the rock desintegration from frost is subject to wide variation and the contrast between day and night temperature is particularly severe. Snow on the mountains and the ice on standing water in the lowlands are normal for June and July.

At elevations of 3800 mm. the "quarrying action" of freezing water is probably felt for five months or more in the year, and above 4000 m. frost may occur any night the year around. Results of frost action is indicated by the amount of talus at the base of Cerros Tembladera, Yunguiyoc, San Cristobal, etc.

B. GLACIATION

Above 4300 m. the landscape has been molded by ancient glaciers. Cirques at the heads of the valleys are characteristic features.

The cross-profile of the valleys show the U-shaped character, with hanging valleys on the sides. Of the U-shaped valley produced by the earlier glaciation, the chief modification has been caused by lateral filling due to development of talus cones and fans. These deposits have a tendency, especially when the valley is in relative soft or fractured rock, to convert the original U-shaped cross profiles into a modified V, which in its complete development, is difficult to distinguish from a normal V-shaped stream valley. However the process has rarely gone far enough to obliterate its original U-form.

Almost all peaks which rise over 4,800 m. are partly covered by glaciers. Those over 5,000 m. usually give rise to extensive ice-fields. The crest of the Cordillera in this section of Peru is not continuously ice-clad, but along the southwestern range, sections of more than 10 km. in length without snow peaks are rare. The icefields on the flanks of several clusters of lofty peaks are comparable to the Cordillera Blanca, but this latter range probably has the most extensive glaciers in Peru.

BOWMAN (1916) pointed out that the glacial features of the Cordillera of Vilcabamba requires a climatic and not the topographic hypothesis. He states:

> "The country west of the Cordillera Vilcapampa* has been reduced to early topographic maturity before the Ice Age, and then uplifted with only moderate erosion of the masses of the interfluves which on the east had passed through the same sequence of events, although the erosion had been carried much further. The reason for this is found in a strong climatic contrast. The eastern side is the windward aspect and receives much more rain than the western side. Therefore, it has more stream velocity and more rapid dissection. The result was that the eastern slopes were cut to pieces rapidly after the last great regional uplift."

The conditions of the glaciers in this area with reference to their state of advance and retreat have been rather uniform, that is, the length and height of the existing glaciers has been approximately constant during the past 40 years. This is in contrast to Central Peru, where almost all glaciers have retreated quite strongly, particularly during the past twenty years.

*Vilcapampa = Vilcabamba

C. DRAINAGE

In the latitude of Vilcabamba the surface of the upland is deeply dissected by the Apurimac and Vilcanota rivers, which carry the water to the Atlantic. The western flank of the Cordillera of Vilcabamba is drained by numerous short streams directly to the Apurimac river. The eastern part is drained toward the Vilcabamba river.

A glance into the Apurimac and Vilcanota canyon shows that the present valley form has by no means been attained by regular progressive growth within a single cycle. To mention only one indication, the various alluvial terraces occupied by small Andean farms typical in these valleys indicate an involved physiographic history.

The rainy season begins in November with daily thunder storms and precipitation reaches maximum between December and March. Irregular rains with cloudy skies are usual in September, October, April, and to a lesser extent in May, the autumn-month of the southern hemisphere.

The discharge of streams during the Peruvian summer is therefore continuous and large in volume. Inasmuch as the cover of vegetation above 2.800 m. is scanty and patchy, the run-off is only slightly retarded and vigorous erosion is common.

The rain which falls in the Vilcabamba region is brought as humidity from the Atlantic (Figure 5), the majority of which is precipitated in the Amazon region or on the eastern flank of the Oriental Cordillera which it encounters. During the summer season the clouds rise higher and pass further to the west, distributing their moisture on the Cordilleras. Part of it crosses the Continental Divide, i.e., the western Cordillera. As a consequence the narrow strip of the Coastal land varying in width from 30 to 70 km. on the western side of the Cordillera is arid, but capable of producing abundant crops when irrigated.

III. STRATIGRAPHY AND PETROLOGY

A. SEDIMENTARY ROCKS

The major rock formations in the thesis area are of Paleozoic age. They will be described in detail.

Precambrian, Cambrian, Ordovician, Silurian, and Devonian formations are not present within the rectangular area of this thesis. However, they have been described beyond the boundaries by many authors (see for example BOWMAN, 1916, FRICKER, 1960) and will be briefly considered. These older sedimentary rocks cover a great part of Peru and South America and comprise the most abundant Paleozoic sedimentary rocks in South America. These Ordovician-Silurian formations are described below.

1. Precambrian and Cambrian

EGELER and DE BOOY (1956) and FRICKER (1960) describe mica-schists as the oldest rocks in the area. These rocks often contain garnet and contain concordant trends of amphibolites. This complex is usually highly folded and foliated. Paragneiss layers are intercalated in more massive gneiss. The occurrence of sandstone gneiss (psammite-gneiss) within the series suggests that all of the material is of sedimentary origin.

According to FRICKER (1960, p. 60) the thickness of the whole series cannot be determined with certainty. But it amounts to several thousand meters. In the upper portions of this series are layers of marble and quartzites.

Cambrian rocks are reported to be absent by FRICKER on the basis of Ordovician fossils found in the sediments immediately overlying the Precambrian rocks.

2. Ordovician - Silurian

According to STEINMANN (1930, p. 15) the Ordovician - Silurian rocks can be subdivided into two major groups:

a. Lower Silurian or Ordovician

b. Upper Silurian

a. Lower Silurian or Ordovician.* The Lower Silurian or Ordovician has a great extent, both in the south and north of Peru, and has been well established on the base of fossil studies.

b. Upper Silurian. STEINMANN points out that Upper Silurian rocks have not been identified in Peru, or very little is known about them. This unit may be present in the Amazon region, to the east of the thesis area.

FORBES (1861, p. 53) first describes it in a very generalized way, as follows:

---

*In the subsequent paragraphs these rocks will be referred to as Ordovician.

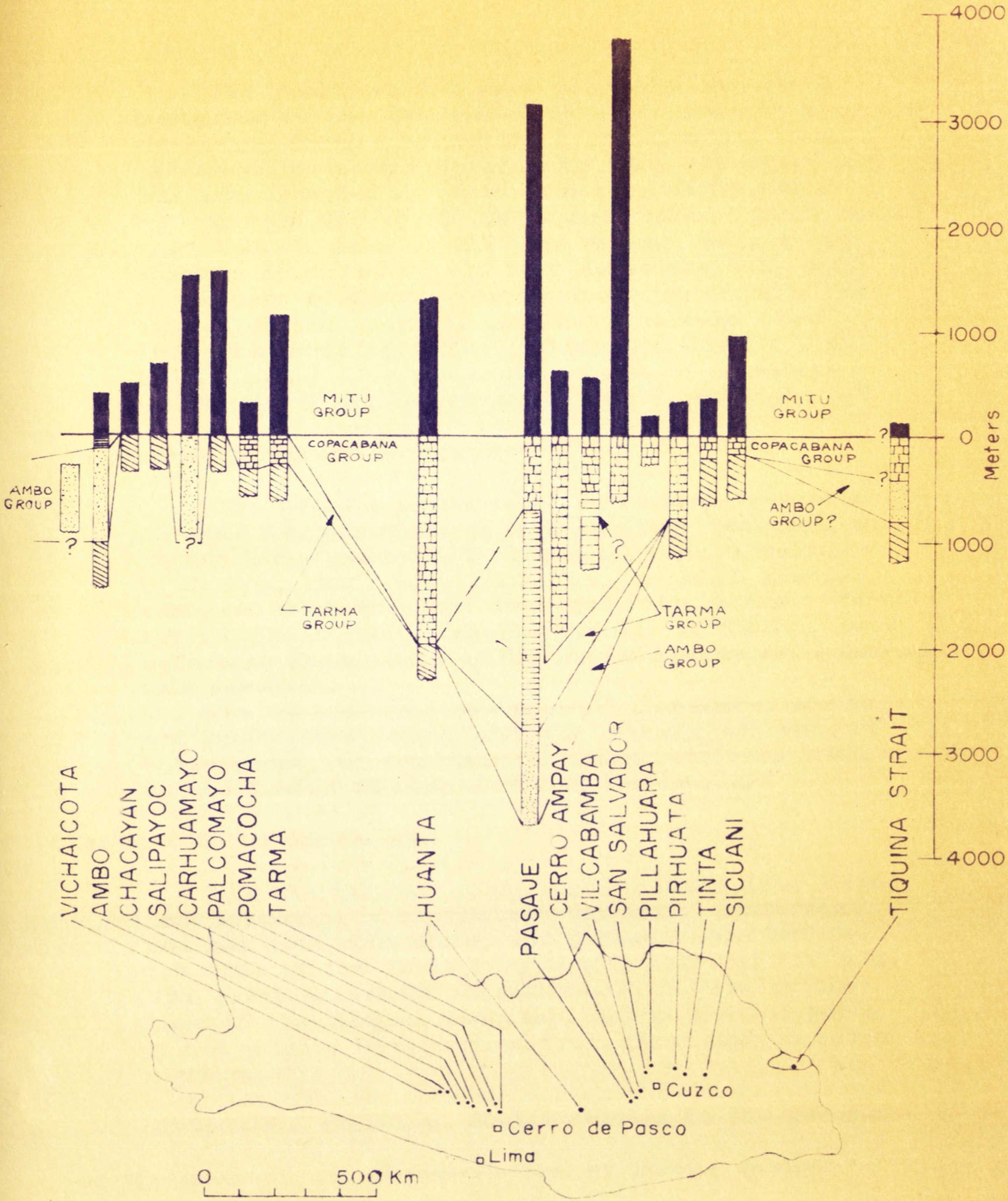


Figure 5. Regional Relationship of Permo-Carboniferous Formations in Peru, after NEWELL (1953, p. 22)

"The rocks which I have grouped together as pertaining to the Silurian epoch show themselves continuously, or very nearly so, over an extent from northwest to southeast of more than 700 miles; and the area occupied by them cannot be estimated at less than 80,000 to 100,000 square miles. They form the mountain chain of the high Andes, rising to an absolute height of 25,000 feet above the sea, and, in the part of South America more particularly the subject of this memoir, continuous through Peru from the north of Cuzco (Vilcabamba lies 150 km. N.W. Cuzco) over the snowy ranges of Carabaya (S.E. Peru) and Appollobamba (N.W. Bolivia)...."

In another paragraph he states:

"The Silurian series in these regions present a physical configuration, as well as other features, so unmistakably analogous to those of their equivalents in Europe, that, notwithstanding the much grander scale on which they are developed, the geologist cannot but imagine himself breathing the air of Siluria, even before an examination of the rocks themselves confirms this suspicion.

The extensive development of clay-slate, shales, and graywackes, along with the metallic contents of these rocks, present mineral characters very similar to the Lower Silurian series in Europe...."

On page 20 he points out:

"As the Silurian origin might indicate (for Peru), this formation is everywhere eminently auriferous, and has been both since, and probably even before, the time of the Incas very largely explored for gold. The great quantities of gold found in Peru at the time of the Spanish conquest, had in greater part, if not wholly, been derived from these diluvial accumulations."

GREGORY (1913a, p. 204) referring to the Silurian on the west of the Cordillera Real of Bolivia quoted:

"The presence of Silurian rests on ten species collected by D'ORBIGNY, none of which are accepted by SALTER as properly determined; five Lower (?) Silurian and fourteen Upper Silurian species, mostly from the Cordillera Real, collected by FORBES and described by SALTER; Ordovician graptolites described by STEINMANN (1904): STEINMANN's collection from southern Bolivia described by ULRICH, and on a collection of graptolites from Santo Domingo...."

BOWMAN (1916, p. 236) reports to have localized Lower Silurian although Urubamba river approximately 100 km. E. of Vilcabamba, but in the absence of fossil evidence, no definitive age can be ascribed to that bed. DOUGLAS (1921, p. 278) reports to have identified a definitive belt of Ordovician graptolite-bearing shales (of Llanvirn age) which seems to be continuous from Bolivia to Inamban district in S.E. of Peru. The more recently and reliable stratigraphic study of the Vilcabamba district was made by the Swiss Geologic Expedition, which in 1960 spent about three months in this area and brought out results in various fields of geology. In regard to the Ordovician formation FRICKER (1960, p. 61) points out:

"The fossiliferous Ordovician consists mainly of black iron bearing slates and of light platy quartzites. At Potrero a few thin and light marl layers enter into the series. The thickness of this series which is also very well exposed at Choquetira (about 16 km straight line from Negrillas) and south of Pampa Soray is about 1000 meters. However, in the north of Chucuito Pass (about 3 km from Negrillas) corresponding rocks could not be found on the top of the

> green phyllites. It is very questionable whether this deposition belongs partly still to the Silurian (Silurian in the strict sense) especially because in the trough of Choquetira the fossiliferous Devonian starts locally with a breccia."

3. Devonian

As has been pointed out in the previous section, this formation along with the Ordovician, reaches great development in the SE of Peru as well as in Bolivia. Both formations seem to belong to a single clastic facies of dark shales and sandstones and their metamorphic equivalents.

According to STEINMANN (1930, p. 20) the Devonian formation has been identified in the region of the Lake Titicaca and extends to Sicuani, S.E. of Cuzco. Also an isolated outcrop has been found in Viroi , department of Huanuco, Central Peru. The thickness of this formation in the Lake Titicaca area is approximately 1000 m. The Devonian beds consist primarily of porous, red to yellow sandstones.

Most of the Devonian units that have been studied are lower Devonian in age (HELDERBERG and ORISKANY, North American Nomenclature according to STEINMANN, 1930, p. 21).

The scarcity of Devonian sediments in Peru is explained by the orogenetic erosion period that took place

Figure 6. Panoramic view of the Vilcabamba Valley with the fog typical for this border zone of the tropical Amazon River basin. (Picture taken from the hut Huamanapi, the base of exploration, 4,200 m. above sea level.)

during the Upper Devonian. It should be emphasized here that in most of the Cordillera region of Peru, Carboniferous beds directly overlie the Precambrian with no intermediate periods represented (STEINMANN, 1930, p. 21).

According to GREGORY (1913", p. 204):

> "The presence of Devonian in the Titicaca region was first demonstrated by the discovery of seven species by D'ORBIGNY, four of which are accepted by SALTER as characteristic of that era. These species, including thee additional ones collected by FORBES, are unlike forms found elsewhere."

MALDONADO (1918) reports a Devonian fauna from the immediate vicinity of Sicuani (S. of Cusco), from black shale; while DOUGLAS (1920, p. 55) suggested that in the Lower Devonian times the sea covered a large tract of the country now forming the Bolivian altiplano and the district north and west of Lake Titicaca. According to the same author during Upper Devonian and Lower Carboniferous times, the country appears to have been elevated above sea-level. But toward the close of the Avonian epoch a further great transgression took place, and marine deposits of Upper Carboniferous and Permo-carboniferous age were laid down over wide areas in the inter-Andean region.

DOUGLAS tabulated the history of the Cordillera as follows:

Figure 7. View of the glacial valley of Vilcabamba, looking east from an elevation of 4,200 m.

-- Deposition of older Paleozoic rocks, up and including the Lower-Middle Devonian
-- Upper Devonian uplift
-- Permo-Carboniferous transgression
-- Permo-Triassic uplift
-- Jurassic transgression
-- Mid-Tertiary uplift, accompanied by a great outburst of volcanic activity.

NEWELL (1953, p. 12) agreed with this tabulation and points out that diastrophism, probably during the late Devonian, was responsible for broad warping and truncation of the area now occupied by the Andes and coastal Peru. He states that there is no record of Upper Devonian in Peru, and the Middle Devonian is limited to a small area within the Titicaca basin. However, in the altiplano of Bolivia, Middle Devonian occurs extensively (KOZLOWSKY, 1923).

FRICKER (1960, p. 61) points out that there is Devonian near the Chucuito-Pass in the Vilcabamba area, but cannot furnish fossil evidence. However, at Potrero 30 km. distance of Vilcabamba Devonian fossils are common.

The complete paragraph is as follows:

Devonian "The youngest beds in the Choquetira basin are Devonian in age. As mentioned already the base is formed locally by a slightly calcareous breccia which contains predominantly quartzite fragments. Above that follow brittle gray quartzite which weather brown as well as gray clay shales. In the middle portion in the series is an approximately 3m. thick, dirty, gray impure limestone bed, with quartzite and shales above it forming the top of the series. The lower portion of the approximately 300 m. thick series contains some fossils, predominantly slightly deformed brachiopod imprints. Especially worth mentioning is an imprint Schuchertella cfs. Agassizi , a type of brachiopod described from the Lower Devonian of Bolivia by KOZLOWSKI in 1923."

Other sediments, probably also of Devonian age, are known N. of the Chucuito Pass S.W. of Vilcabamba. Sediments of Upper Devonian and Mississippian age could not be proven to be present in the area studied.

4. Permo-Carboniferous

a. Ambo group (Mississippian). Mississippian rocks have not been established with certainly in the Vilcabamba area. No one has so far dedicated himself to this problem. However, the writer believes that the two major systems of Carboniferous (Mississippian-Pennsylvanian) are most probably present in the area of the Vilcabamba mining district. The basic reason for this statement is twofold; although both of them are not conclusive.

1. Carboniferous (?) plants, poorly preserved, were collected at Orocomorjo (AGUILAR, et al., 1957, p. 13) between Pampaconas and Vista Alegre, which is about 10 km. west of Vilcabamba. The plant-bearing shale beds were fragile and carbonaceous. No detailed determination was carried out. Since no plant fossil has been reported for the Devonian in Peru, therefore, these rocks are tentatively assigned to the Mississippian.

2. At Negrillas, which is the southernmost point of the present work, the phyllites are directly overlain by a pinkish conglomerate. The conglomerate is composed of quartzite, quartz and phyllite pebbles within a silty matrix. The conglomerate pinches out toward the east of Negrillas, which suggests a lenticular character and a variable lithologic sequence. It now seems proper, in view of the lithologic similarity and stratigraphic position, that this bed should be classed as Mississippian, i.e., as Ambo group.

The nearest Mississippian (Ambo group) occurrence is at Pasaje, about 18 km. northwest of Abancay and about 100 km. west of Vilcabamba.

In fact, NEWELL (1953, pp. 11, 13, 31) shows a picture of the Pasaje, Ambo group outcrop and gives the following sequences:

"Mississippian, Ambo Group

3. Shape and interbedded sandstone, brick red, estimated at 1000 feet.

2. Conglomerate, massive, red and brown composed of boulders up to 2 ft. in diameter of quartzite, granite, andesite, limestone, in matrix of coarse quartz sandstone, makes conspicuous hogback parallel with the Apurimac River, estimated at 2,000 feet. Total Ambo group, 3000 feet."

Referring to the lithology of Pasaje NEWELL adds (p. 11):

"The lower two-thirds are massive beds of conglomerate in a matrix of coarse brown sandstone (pl. 1, pl. 2, Fig. 2), grading upward into interbedded red sandstones and red shales. Lithologically more like the Ambo of central Peru are coal-bearing clastic beds at the base of the marine lower Permian near Tiquina strait, on the Peruvian-Bolivian border, Lake Titicaca. About 700 feet of beds overlying the Devonian are provisionally referred on lithologic grounds to the Ambo group. Lacking paleontologic evidence it is necessary to recognize, however, that these rocks may as well belong to the Pennsylvanian or to the lower Permian."

It must be emphasized that Pasaje lies in the lowermost part of the slopes at the Vilcabamba Cordillera. Conclusive evidence of Mississippian age was found at Ambo, department of Huanuco (STEINMANN, 1930, p. 28) and in different outcrops between Huanuco and Tarma. The lithology is described as consisting of gray to greenish shaly slate, sandstone, and conglomerates. These beds usually contain plant fossils and occasionally thin beds of coal.

The more common plant fossils found are:

1. The Lycopodiales of which the most common members of this group are Lepidodendron, Bothrodendron, and Sigillaria.

2. The Equisetales; only the tree-like Calamites are reported to be found.

3. Pteridosperms; these plant remains show a striking resemblance to modern ferns; only the Sphenopteris was found.

It must be remembered, however, that the material available for this study is usually very incomplete, and consequently it is a matter of considerable difficulty to piece together the fragmentary record and obtain a clear picture of each and every kind of plant that is found in the Mississippian Period. All evidence of external forms which can be gained from the plant impressions, such as the manner of branching, the nature of the foliage and the kind of surface ornament, must be considered together with the details of internal structure obtained from thin section of favorable petrifications.

Returning to the psephite character of the Mississippian (?) strata of Negrillas, it corresponds to the Upper Devonian orogenesis. After this the rugged relief was covered by the transgressive sea and sedimentation of neritic character is expected. This transgression corresponds to the nearshore marine portion.

The area of Negrillas Lake appears to be critical for a correlation of Upper and Middle Paleozoic series (see Figure 9).

For the psephitic nature and the other reasons indicated a Mississippian (Group Ambo) age for the basic conglomerate of Negrillas is postulated.

b. Tarma Group (Pennsylvanian). The thickness of the limestone unit in the thesis area is approximately 2000 m. Fossils of the Upper Carboniferous to Lower Permian are present. The great thickness and the contained fossils prompts a subdivision of this limestone sequence into two different time groups, the Tarma group (Pennsylvania) and the Copacabana group (Lower Permian), instead of the Copacabana group of Upper Paleozoic age as suggested by some.

Some authors used the name Copacabana to include both Pennsylvanian and Lower Permian. There is no general agreement as to the limits of the Copacabana group to date. In the suggested subdivision of this report, the two groups will be defined.

The following is a brief description of the Tarma group within the thesis area. In the Negrillas area a pinkish conglomerate is directly overlain by a thin coarse sandstone, on which in turn a massive limestone is deposited. (For full details see AGUILAR, 1957, p. 5) The limestone occurs along the north side of Negrillas fault, but to the east of Negrillas Lake, it is located on both sides of the fault.

In its lowermost part the limestone is interbedded with sandstone, but upwards the sandstone beds practically dissappear. This basal unit may reach a thickness of 800 m. and tentatively is considered by the writer to be the Tarma group. The stratigraphic position, the lithologic character, and the fossil content support this classification.

The above limestone overlies the conglomerate, previously described as belonging to the Ambo group (Mississippian). As noted, the lithologic character of this group, at least at its base, consists of coarse sandstone, mainly composed of rounded grains of clear quartz and designated as conglomeratic sandstone. As the sandstone increases in thickness toward the south and southeast of Lake Negrillas, the sandstone grains become finer. Cross-bedded sandstone is usually present at the base of the interbedded sandstone-limestone layers.

NEWELL (1953, p. 13) points out:

> "In general the textures of the Pennsylvanian rocks, are finer than those of Mississippian. Conglomerates are uncommon; such pebbles as have been observed are very small and are composed of local intraformational

Figure 8. View of the Calderon area, consisting of the top of the Copacabana group. The topographic system of gullies to the right follows the Calderon fault. Immediately following to the left is the skarn mass with acutely intersecting features. The skarn alteration decreases toward the cliff on the left.

> materials. Hence, it is concluded that the marine transgression of Middle Pennsylvanian time found the western part of the continent relatively low. CHRONIC's studies, Part II, of this report, reveal close affinities between the Tarma faunas and those of the Pennsylvanian of the Middle Amazon in Brazil described by Derby (1874)."

BOWMAN (1916, p. 322) probably was the first to suggest that these rocks of the Vilcabamba area might belong to the Pennsylvanian.

The nearest Tarma group occurrence to the north is at Pasaje, about 100 km. NW of Vilcabamba. NEWELL (1953, p. 30) describes it as concordant and without evidence of a hiatus on Ambo group beds. He tentatively estimates the thickness at 2000 m. (6,882 feet). NEWELL *et al* (1953, p. 46) describes the Pasaje outcrops as follows:

> "PASAJE (loc. 300): A few silicified fragmentary bryozoans and fusulinids were recovered from the lower beds of this section. The fusulinids suggest that these strata are of earliest middle Pennsylvanian age. The excellently preserved bryozoan fragments bear closest affinities with species described by Moore from upper Pennsylvanian strata of north Texas. Lower and Middle Pennsylvanian Bryozoa of North America, however, are poorly known, so close comparison cannot be made."

At Tarma, the type locality, the thickness reaches 300 m. (980 feet). DUNBAR and NEWELL (1946, p. 385) described and defined at Tarma a Middle Pennsylvanian (Moscovian-Des Moines) fauna. Guide fossils from these beds include *Neospirifer* cf. cameratug, Chatetes sp., and *Fusulinella peruana* (MEYER).

FRICKER (1960, p. 61) points out:

"Pennsylvanian(?) - Permian - : the probably Lower Devonian schists and quartzite in the north of Chucuito-Pass (3 km SE of Negrillas) are directly overlain by the Copacabana Group. At Negrillas, south of Vilcabamba, this Tarma sequence starts with a conglomerate which contains mainly quartzite components. At South Tincos, however, the basal part consists of thin dark shale mainly followed by reddish slightly sandy coarse grained limestone. At the middle and upper locality fusuline limestone and predominantly dark gray partly dolomitic echinodermal limestone are 5 to 10 cm. thick, with chert. The Copacabana group reaches a thickness of more than 1500 m. south of Vilcabamba which occurs in northeast direction, where together with decrease in thickness shale content increase."

In another paragraph he states:

"From the comparison with other localities it seems likely that the basal portion of this sequence still belongs to the Pennsylvanian, the major portion however is Lower Permian."

Fossil references include that of BOWMAN (1916, p. 322) who points out:

"All of the Upper Carboniferous lots of fossils represent the well known South American fauna first noted by D'ORBIGNY in 1842, and later added by ORVILLE DERBY. The time represented is the equivalent of the Pennsylvanian in North America."

He gives the following list of fossils (which is of course not well arranged according to modern standards):

Pampaconas (Pampaconas Valley near Vilcabamba)

Lophophyllum

Rhombopora, etc.

Productus

Camarophoria (common)

Spirifer condor D'ORBIGNY

Hustedia mormoni (Marcon)

Euomphalus (Large form)

Most of these fossils belong to Lower Permian in NEWELL's (1953) Upper Paleozoic study. However, the Negrillas location to which tentatively I have assigned a Pennsylvanian age, lies southeast of this area and unfortunately no faunal study has been made.

FRICKER (1961, p. 61) collected at Tincoc near Vilcabamba the following fossils:

Echinoderm fragments

Hustedia sp.

Dictyoclostus

During prospecting for radioactive minerals several fossils were collected from the middle portion of the limestone. From these two species were identified by Miss ROSALINE RIVERA (1957, p. 15): Linoproductus cora d' ORB' and Hustedia meridionales CHRONIC et al.

According to NEWELL (1953, p. 89) the first one belongs either to the Pennsylvanian or Permian, while the second one has been found only in the Lower Permian.

A section of Upper Paleozoic rocks was studied near Munani, north of Lake Titicaca. This sequence of several thousand feet of dark gray shales and interbedded limestone was supposed by DUNBAR and NEWELL to represent a higher part of the Permian. Actually NEWELL and CHRONIC found that it contains Middle Pennsylvanian fossils.

The following fossils appear to be especially diagnostic as indicators of Middle Pennsylvania:

Profusulinella spp.	Cinclidonema sp.
Fusulinella spp.	Pseudoparalegoceras peruvian
Neospirifer cameratus	Chaetetes sp.
Spirifer aff. S. opimus	Rhipidomella penniana

A comprehensive study of Pennsylvanian and Permian marine faunas has not been undertaken and should be highly recommended.

c. Copacabana Group (Upper (?) Pennsylvanian - Lower Permian) Definition. The name Copacabana Group was introduced in 1936 by LA ROSA and PETERSEN. The type locality is the Copacabana peninsula in the Lake Titicaca. Originally the name Copacabana Group was applied to the upper portion of the limestone section at the strait of Tiquina, and Recreo Group for the lower part, which was judged by them to be Lower Carboniferous.

More recently, NEWELL (1953) has demonstrated that the entire strata belongs to Lower Permian, and has proposed the term of Copacabana, as a name for the whole

Figure 9. Partial view of Negrillas Lake showing prominent limestone units of Pennsylvanian and Lower Permian age (looking east). Elevation above sea level: 4,000 m.

Figure 10. View of the upper portion of the Vilcabamba area. The hill in the foreground is called Huamonapi. The length of the entire panoramic crest is about 2 km.

sequence. The following definition is given for the Copacabana Group:

> "The most important division of the Upper Paleozoic in Bolivia and Peru belongs mainly to the Lower Permian Wolfcampian series. DUNBAR and NEWELL (1946, p. 394-395) recently have defined and described the Copacabana group as embracing the lower Permian beds of the Central Andes in Bolivia and Peru."

However, this definition is somewhat modified in their next paragraph.

> "Copacabana Group embraces the entire upper Paleozoic sequence above the Devonian."

Hence they propose to limit the term Copacabana Group to the marine section, mainly limestone, between the lower, coal-bearing Ambo shales, and sandstone and the upper red Tiquina sandstone classed with the Mitu group. This definition should involve Carboniferous to Lower Permian.

In this study, the author proposes to restrict term Copacabana Group to the Lower Permian.

The Copacabana group in the area of Vilcabamba is characterized by the predominance of massive limestone and minor amounts of sandstone beds. The basal portion near the Pacopata camp (see geological map in Appendix) is limestone, very silicified, with occasional thin beds of siltstone. The fossils here are mostly well preserved brachipods. The upper part of the limestone, located toward the north flank of the Cerro Huamanapi, has been strongly altered, with the development of garnet, epidote, hematite, i.e., a skarn-type zone. The grade of metamorphism conspicuously increases closer to the igneous body. Beyond a certain line no limestone is found, instead, only epidote, garnet and iron oxides are present.

Approximately in the center of the lower limestone, cherty limestone beds are almost parallel to the main uranium-bearing outcrop (San Marcos, Trinchera, Esperanza).

The fossils characteristic of the Copacabana group have been mentioned in the preceeding chapter. These leave no question in regards to the age of the enclosing rocks. The thickness of the Copacabana Group is about 800 m. This group reappears as isolated outliers at Pampaconas and Pucyura, both within a radius of 4 km. from the Vilcabamba. village.

It has been previously stated that BOWMAN (1916) was the pioneer stratigrapher and geographer in this area. He used the name Upper Carboniferous only. Dealing with this group, he pointed out:

> "Both the enormous thickness of the Carboniferous limestone series (the largest part of these strata now is considered Permian) and the absence of clastic members over great areas in the upper portion of this series proves the widespread extent of Carboniferous seas and their former occurrence in large interlimestone tracts from which they have since been eroded."

The wide distribution of the Copacabana limestone, together with the uniformity of the fossil fauna suggest that the sea extended entirely across the Andes region (see PETERSON, Map Fig. 5). Nevertheless, they appear somewhat monotonous and thus point to a shallow water sea environment.

Northwest of Vilcabamba, occurrences of the Copacabana Group have been described in various places. Near the Apurimac Valley an exposure of the Copacabana Group is found on Cerro Picchu, 35 km. west-north-west of Abancay, where the limestone series is about 830 m. thick. At Pasaje, 37 km. northwest of Abancay, below the massive limestone of the Copacabana Group, several thousand feet of relatively unfossiliferous black shales and interbedded thin limestone are assigned to the Tarma group. At Huanta probably the most abundantly fossiliferous Permian section is exposed. Brachiopods, bryozoans, and fusulines of considerable abundance occur at innumerable horizons, and corals and large gastropoda are found sparingly at many horizons.

Southeast of Vilcabamba occurrences of the Copacabana Group have been recorded in other localities. In Vilcanota Valley, exposures of the Copacabana group and overlying Mitu volcanics and red beds occur intermittently in the canyon walls of the Vilcanota river from its source in the massif of the Nudo de Vileanota downstream to Ollantaytambo, a distance of 200 km (NEWELL, 1953, p. 15). In fact, outcrops of Upper Paleozoic have been measured at Cerro Pirhuate between Sicuani and Urcos, at San Salvador about 20 km. northeast of Cuzco, and at the strait of Tiquina. The most exhaustive work so far, in regards to the Lower Permian in Peru, is the study on fusulines by NEWELL, CHRONIC and ROBERTS (1953) in their book on the Upper Paleozoic of Peru.

d. Mitu Group Middle Permian (?). A thick series of volcanic rocks, red arkosic sandstone, coarse clastics and minor amounts of shales rests unconformably on the Copacabana Group (see Figures

The red to brown volcanic series occupies a definite belt of at least 5 km in length, covering a continuous area between Tincoc to Minasmayo. The term "volcanic rocks" is used in a broad sense. Field conditions suggest that both extrusive and intrusive characteristics are present at various localities. Both in Cerro San Critobal and Minasmayo these volcanics appear to be capping the Copacabana limestone formation. However, at Calderon lagoon arkosic sandstones of probably early Copacabana age appear to be uplifted by this series of red "volcanics". This formation is of variable thickness.

The volcanic sequence is prominently exposed at Cerro Chojantirca, Cerro San Cristobal and Cerro Simacocha, where it reaches its greatest thickness and extent. To the northwest, the volcanic series decreases both to the north and south. At Minasmayo only a narrow belt of volcanics is present. The clastic sediments increase towards the northwest. In most of the outcrops of the area the volcanic rocks appear to cap the limestone and its proximity is noted by an increase of Fe-Mg minerals, very conspicuously between Cerro Tembladera and the ravine of Calderon. The thickness at Chojantirca or San Cristobal reaches probably 500 m. Red sandstones and coarse clastics outcrop at Minasmayo and Collpa, although the thickness does not match that of the volcanic series. Agglomerates are developed in the south of the Lagoon of Minasmayo but only in local spots (see geologic map). The development of this agglomerate may be a function of the local relief of the surface, thus being well-developed in the low areas of a rugged topography. Most of the components are weathered pebbles of the porphyric country rocks. The age of the red shaley-sandstone in the northwest of Minasmayo has not been quite established; however, tentatively, they are assigned to Mitu age. In the area surrounding the Collpa pass red sandstone of Mitu age is widespread.

FRICKER (1960, p. 62) discusses the thickness and variation of this gradational Mitu group, at Vilcabamba and points out:

"On the basis of several fossil discoveries the Middle Permian age of the widespread group of beds could be proved by them (HARRISON, 1943; DUNBAR and NEWELL, 1946).

Within the reach of our area of work the Mitu-group is very typically exemplified near Vilcabamba. As mentioned before it follows the Copacabana Limestone. In the lower part red marls and shales predominante. Then however, red sandstone and breccias also follow. Volcanic rocks further play an important role; thus the sediments south of Vilcabamba are cut by eruptive rocks. Under the microscope melaphyre* is seen, which occurs southwest of Tincoc, and quartz prophyry from the surroundings of the village of Vilcabamba can also be recognized. That these acid to basic eruptions were contemporaneous with the deposition of the sediments, is indicated by the composition of the components of the conglomerates and breccias, which contain also volcanic material. The zone of eruptive rocks south of Vilcabamba has only a limited extent; in the southwest of this village corresponding outcrops are lacking.

As this description shows, the Mitu-group exhibits a remarkable similarity with the Verrucano of the Alps. The thickness of this section of strata amounts to several meters in the valley of Vilcabamba; unfortunately, the northern limit could not be determined precisely due to a lack of time.

West of Vilcabamba there is a thin horizon of gravel which contains well preserved brachiopods. They were determined to be Marginitera Capaci D'ORBIGNY (compare NEWELL, 1953). Since the Mitu strata developed from the lower Permian Copacabana limestones, this series may have originated in the Middle Permian. NEWELL, CHRONIC and ROBERTS pointed out in 1953."

The name Mitu was applied to the red sandstones and conglomerates at Cerro de Pasco by McLaughlin in 1924 (p. 600) and the term Yauli was applied by him for a volcanic phase of the Mitu beds near Tarma. NEWELL et. al. (1953, p. 18) recommends that of the various terms applied

Figure 11. The E-W, Negrillas fault, which extends clearly 3 kilometers. The fault at the limestone portion showed weak radioactive anomalies.

to this Permian red bed succession, the name Mitu should be adopted mainly because of its long established use in Central Peru.

The nearest outcrop of the Mitu Group is located in the area of Salcantay where it extends at least over a distance of 50 km. It also outcrops at Vilcanota, SE of Vilcabamba, over a length of 100 km. from the Nudo de Vilcanota to Ollantaytambo (NEWELL, 1953, p. 19). This group is very widespread throughout North and South Peru and everywhere rest unconformably on the underlying strata.

KATZ (1959, p. 46), dealing with the Permian, stated:

> "A second period of orogenic movements follows after the Middle Permian, when Young Variscan diastrophism created the Gondwanides; these extend from the Argentina through Bolivia into Peru. In a detailed section it is shown how the Permian sea ended in a regressive phase, its marine deposits, although still rich in fossils, suddenly mixed with red material apparently derived from nearby terrestrial sources. Coarse red clastics unconformably overlie the Permocarboniferous limestone and shales at a regional scale; the thick synorogenic deposits are associated with rhyolitic and andesitic effusives. For the Permo-Trassic Period, great erosion thus is ascertained, and the thick sandstone series which trends along the northeastern Andean slope unconformably, covers the Lower Paleozoic which is correlated with this period. It seems to be the northwestward extension at known Gondwana deposits in Bolivia."

The Mitu group at Vilcabamba is closely similar to these units described by KATZ.

B. IGNEOUS ROCKS

1. Introduction

The rock samples for this study were collected in different locations which are all marked in the geological map, except for numbers 2-A and 2-B. These two samples were collected in the Machupiochu batholith, the main granitic batholith near the thesis area, and at the same time the larger granite batholith in SE-Peru.

The rocks number M-4, M-5 and M-6 belong to the volcanic rocks of Mitu age. Those numbered M-1 and M-2 come from the small plugs and the number M-3 and M-16 from the dikes. Under the microscope M-1, M-2 and M-3 showed to belong to a similar rock type with gradational changes of composition. The sample number A-15 belongs also to a small plug near Andrianita prospect. Rock C-7 is a portion of the skarn rock in the Calderon fracture zone (lower part) and the rock number C-9 belongs to the actual skarn zone in Calderon.

Chemical analyses have been made for the following six rock samples: 2-A, 2-B, A-15, M-1, M-2 and M-3.

For the purpose of comparison all other rock analyses available from Permian rocks were collected and entered into the standard diagrams used by most European petrologist (so-called NIGGLI diagrams). In this comparison, the rocks of the present present thesis were re-numbered. The new numbers simply correspond to the chronological sequence of rock analyses from Peru. For the location of the 47 rocks analyzed previously see the respective papers given in the Bibliography. Analyses 1 to 36 were previously discussed and summarized by G. C. AMSTUTZ (1960).

The six new rock analyses for this paper were prepared by Dr. Max WEIBEL of the Geochemical Laboratory of the Swiss Federal Institute of Technology in Zurich, Switzerland. The author wishes to acknowledge the coopera-tion of Dr. Weibel at this time.

2. Individual Samples

On the following pages the individual samples are des-cribed in detail. Typical and special features are shown on photographs.

Specimen number: 2-A (48)

Location: Machupichu, Cuzco, Peru

Megascopic Character: Coarse grained light rock with occasional dikes and zones of 2-B.

Microscopic Character:

I. Main Constituents:

K-Feldspar (45%): Microcline perthite, combined earls-badalbite twins in coarse grains, containing small inclusions of altered plagioclase. Partly altered to clay minerals.

Plagioclases (20%): Oligoclase-albite (An_{10}), subhedral grains, some of them are enclosed poikilitically in the feldspar; partly altered to sericite and saussurite (?).

Quartz (25%): Anhedral and interstitial to feldspar; sometimes distorted and broken, ondulatory extinction.

Biotite (8%): Brown, birds eye extinction, intergrowth with, and overgrowth of muscovite.

II. Accessories (2%): Pyroxene, chlorite, zircon, apatite, magnetite, epidote, tourmaline.

III. Rock name: Granite to granodiorite.

Specimen number: 2-B (49)

Location: Machupichu, Cuzco, Peru.

Megascopic character: Medium grained massive rock in the biotite and hornblende in a white matrix of plagioclase and quartz.

Microscopic character:

I. Main constituents:

Plagioclases (60%): Subhedral to euhedral zoned crystals of andesine-oligoclase, normal zoning, selective alteration has accentuated this zoning; sometimes these zoned feldspar occur in peculiar cruciform twins.

Quartz (17%): Anhedral, interstitial to feldspar; inclusions are abundant, particularly of amphiboles (euhedral).

Biotite (15%): Contains many inclusions, particularly of the accessory minerals such as apatite and zircon. Biotite in places appears to replace hornblende.

Hornblende (6%): Pleochroism greenish brown.

II. Accessories (2%): sphene, chlorite, apatite, magnetite.

Rock name: Quartz diorite.

Figure 12. Dike on the upper part of "San Marcos" prospect, Huamanopi zone. The dike strike northerly and dip almost vertical with tendency to the west. Thickness about 3 m. At the bottom partial cliff of the Huamanopi hills.

Sample number: M-1 (51)*

Location: Huamanapi, 200 m. west from Pacopata camp, Vilcabamba district, Cuzco Department, Peru.

Megascopic characters: A fine-grained, blackish gray rock. Abundant biotite is inside.

Microscopic character:

I. Phenocrysts:

Biotite (15%): Euhedral forms with the faces (001) and (010), yellow-brown to reddish brown pleochroism; size of grains 1. to 2. mm. (in the handspecimen up 4 mm.); unaltered.

Augite (5 %) : Irregular forms, light green, weak pleochroism and characteristic cleavage. Some crystals altered to chlorite and other to a mixture of chlorite-serpentine-talc.

II. Matrix (75%) : Consists of extremely small indistinct grains of probable plagioclase, biotite, pyroxene, epidote, chlorite, and some accessory minerals.

III. "Bubbles" (5%): Bubbles of calcite up 3. mm. in size, surrounded or bordered by chlorite and talc (?), in these cases containing opaque grains. Opaques disseminated through groundmass. Some vesicules display a peculiar idiomorphic shape, but are filled

*The first number refers to the hand specimen; the one in parenthesis to the rock analysis; not all specimens were analyzed chemically.

with calcite, talc and no opaques. It is questionable whether these opaques represent highly altered early olivine.

IV. Rock Name: Trachyandesite

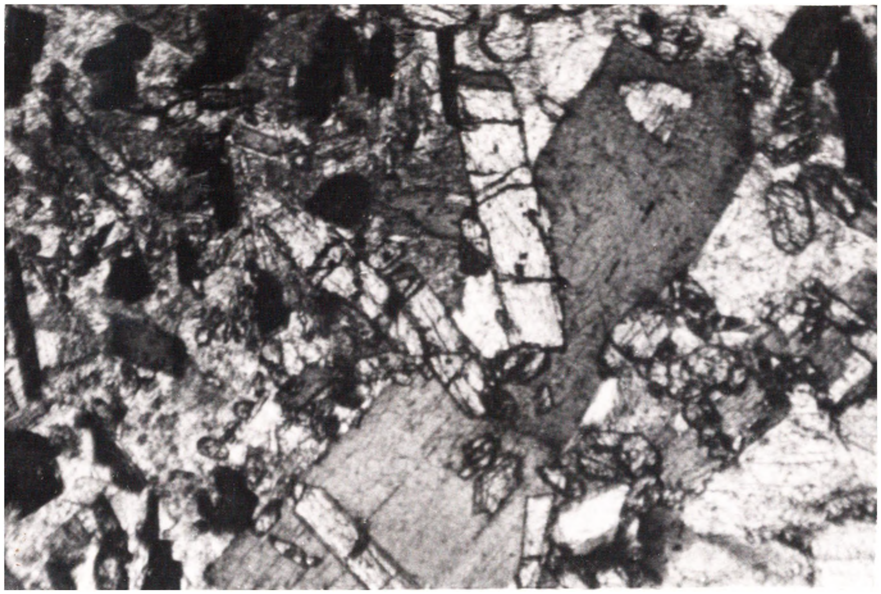


Figure 13a. Sample 51 (M-1). Augite (high relief) partly inclosed in biotite. 50X, plain light.

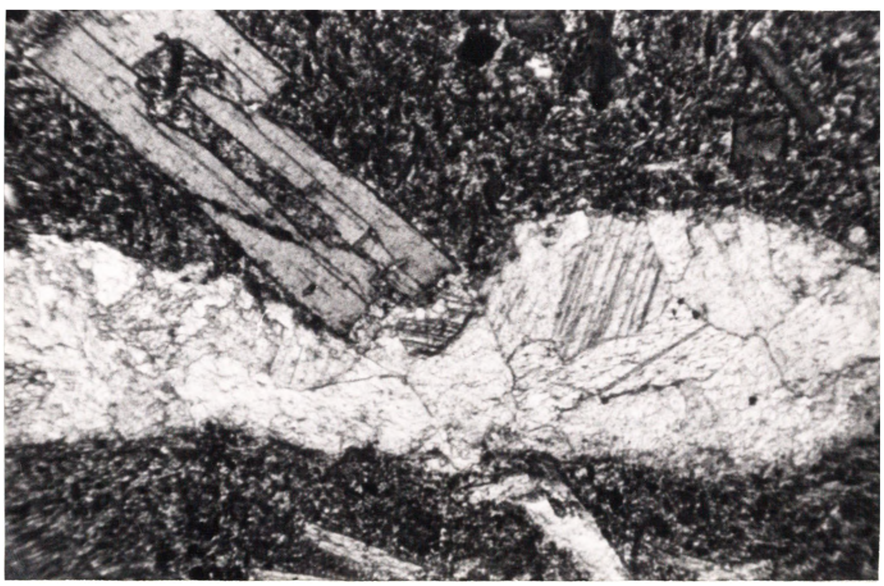


Figure 13b. Sample 51 (M-1). Calcite of probable foreign origin abundant. Euhedral biotite includes groundmass. 50X, plain light.

Sample number: M-2 (52)

Location: Cerro Yunquiyoc, 300 m. NW from Pacopata camp, Vilcabamba district, Cuzco, Peru.

Megascopic characters: Fine-grained, greenish felsic rock with disseminated grains of pyrite.

Microscopic character:

I. Phenocrysts: Plagioclase (60%): Bytownite (75An); euhedral to sudhedral; showing little alteration; grain size predominantly uniform (about .4 to .8 mm. in length).

II. Matrix (30%): Fine silt-like ground mass probably composed of plagioclase, epidote (?), chlorite.

III. Accessories (4%): Opaques (pyrite?) either as isolated or clustered grains.

IV. "Bubbles" (6%): Calcite, (or dolomite) sometimes associated with garnet, epidote, chlorite, talc, pyrite (?). Note: this rock has transected limestone and probable picked up calcium for garnet and calcite.

V. Rock name: Lampsophyre

Sample number: M-3 (53)

Location: 200 m. north of Aurora; Vilcabamba district, Cuzco, Peru.

Megascopic characters: Greenish gray, fine-grained rock. Abundant biotite scattered throughout the groundmass. Veinlets of calcite of probable foreign origin.

Microscopic character:

I. Main mass:

Plagioclase (70%): Albite (16 An) contains homogenously distributed cloudy alteration products; grouped cluster-like ("arborescent fabric"), grain size up 0.8 mm.

Biotite (15%): Euhedral forms: size up to 1.5 mm. Pleochroic ranging from light to dark brown; occasionally intergrown with opaque grains.

Augite (8%): Weak pleochroism from colorless to weekly greenish; anhedral shape but typical cleavage, rather scattered in the section.

Opaques (2%): Grains almost all about the same size (50 microns); shape often square, but also irregular.

II. Patches, "bubbles" (5%): Calcite up 1.2 mm., chlorite after olivine (?) moderate pleochroism.

III. Rock name: Keratophyre to albite-Camprophyre

Sample number: M-4

Location: 1 km. west of village of Vilcabamba Choquepata area, Vilcabamba district, Department of Cuzco, Peru.

Megascopic description: A brownish-reddish rock with numerous lath and needle shaped phenocrysts of plagioclase, which are also slightly brownish due to content of hematite. Size of phenocrysts 0.3 to 1.3 cm.

Microscopic character:

I. Phenocrysts: Plagioclase (40%): Elongate euhedral to subhedral phenocrysts of labradorite (68 An). Incipient saussuritization (Figure 14).

II. Matrix (40%): The groundmass is composed of a fine moss-like crystalline aggregates of plagioclase, hematite and indefinite amounts of quartz and K-feldspar (grains altered and obscured by the mossy limonite).

III. "Patches" (20%): Calcite of probable secondary origin; not clearly amygdaloidal; often surrounded by a mass of limonitic semi-opaque material, possible origin in place from altered mafics.

IV. Rock Name: Melaphyre

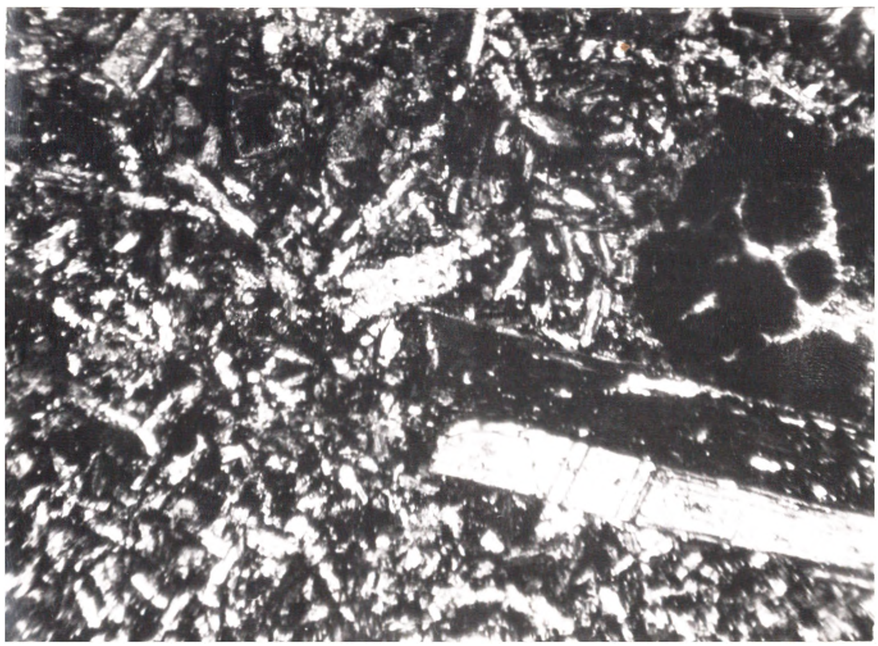


Figure 14. Sample M-4. Phenocryst of plagioclase embedded in a finely crystalline groundmass with a "mossy" distribution of limonite. 50X, crossed nicols.

Sample number: M-5.

Locality: 1 km. west of Vilcabamba village Choquepata area, Vilcabamba district, Cuzco, Peru.

Megascopic description: Dark brown, porphyritic rock. Contains euhedral to subeuhedral plagioclase phenocrysts, ranging in size from 0.2 to 1.7 cm.

Microscopic character:

I. Phenocrysts Plagioclase (30%): Labradorite (63 An), very weakly altered and containing interstitial calcite or quartz, and grains of iron oxide.

II. Matrix (50%): Groundmass shows tendency to fluidal texture. Fine-grained opaques abundant (mostly hematite with some magnetite). Numerous very small plagioclase needles visible.

III. Patches (20%): Mostly calcite and somewhat less quartz. As in sample M-4, the patches are rather irregular and appear to be connected with the fracturing and perhaps the extrusion or intrusion of this rock. They are probably material picked from traversed wall rock. Essentially, the minerals of this sample are similar to those in sample M-4; the difference is texture of the groundmass, and increase of the relative amount of quartz.

IV. Rock name: Melaphyre.

Figure 15. Sample M-5. Plagioclase showing carlsbad, polysynthetic and interpenetration twinning. Size of phenocrysts 0.3 - 1.3 cm. 50 X, crossed nicols.

Sample number: M-6

Location: 1 km N of Aurora, Calderon area, Vilcabamba district, Cuzco Department, Peru.

Megascopic characters: Gray-purple rock, occasionally with red spots. Predominantly equigranular.

Microscopic character:

I. Phenocrysts:

Orthoclase (25%): Some intermediate to smaller phenocrysts may be orthoclase; now completely covered with fine scaly alteration products. They suggest orthoclase as an original mineral due to their constant isomorphic shape and the abundance of a sericitic alteration product.

Plagioclase (30%): Elongate euhedral grains up to 3 mm. Alteration zoning with a clear rim in some (Figure 16b), absent in others; incipient chloritization in some grains; but most of the alteration minerals are extremely small.

Augite-ghost grains (5%): Now consisting of pseudomorphis filled with Fe-oxide, chlorite, serpentine, and perhaps bowlingite-iddingsite.

II. Matrix (60%): Size of grains range from small to very fine orthoclase (?), plagioclase (predominantly), altered augite, iron oxides, chlorite.

III. Inclusion (2.5%): One grain of hypidiomorphic quartz (Figure 16a) with a reaction halo of chlorite, a brownish indistinct mineral, and needles of grammatite (?) or cristobalite (?).

IV. Rock name: Melaphyre.

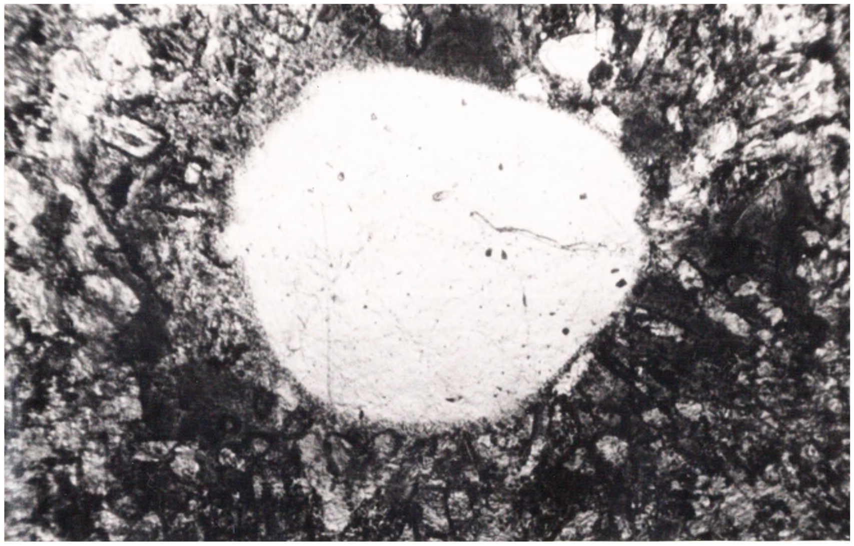


Figure 16a. Sample M-6. Hypidiomorphic grain of quartz with a reaction halo of chlorite and other minerals. 50X, plain light.

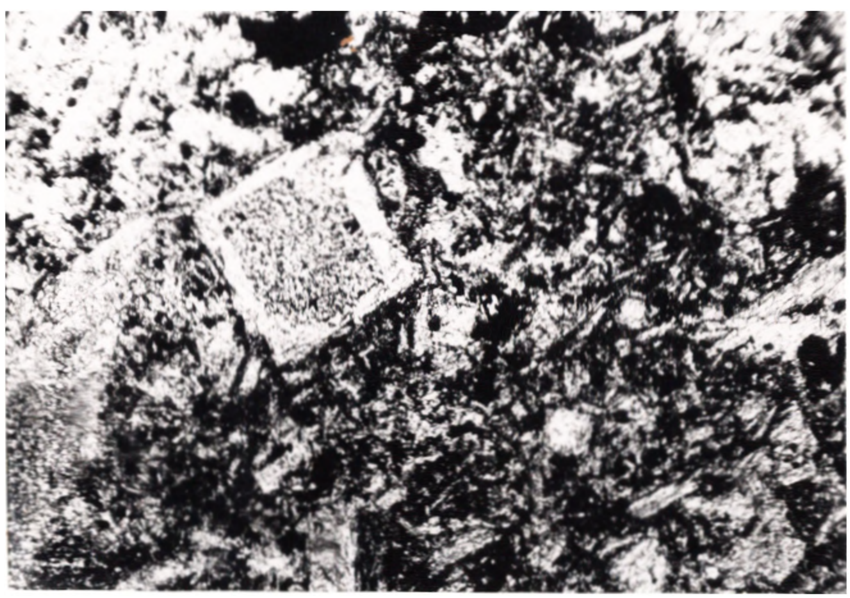


Figure 16b. Sample M-6. Plogioclase showing a clear outer zone. Abundant iron oxides in the groundmass. 50X, plain light.

Sample number: C-7

Location: Calderon prospect (lower part), Vilcabamba district, Cusco department, Peru.

Megascopic characters: Dark red rock characterized by the fine-grained matrix; some spots of calcite seen; pitchblende, pyrite and hematite contained as ore minerals.

I.. Constituents:

Apatite (50%): Euhedral crystal forms; size up 2 mm. (Figure 17a and b).

Quartz (5%): Rather scattered; characterized by ondulatory extinction.

Calcite (40%).

Chalcopyrite, pyrite (?) and pitchblende (5%).

II. Rock name: Apatite-felsite.

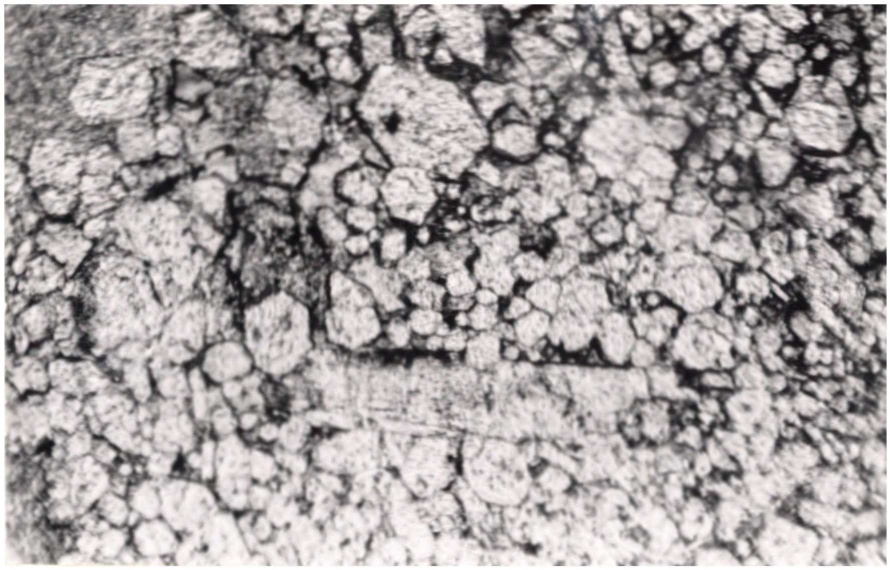


Figure 17a. Sample A-7. Apatite showing six-sided prismatic crystals. Abundant apatite developed during the metamorphism of limestone. Location: Calderon Bajo. 50X, plain light.

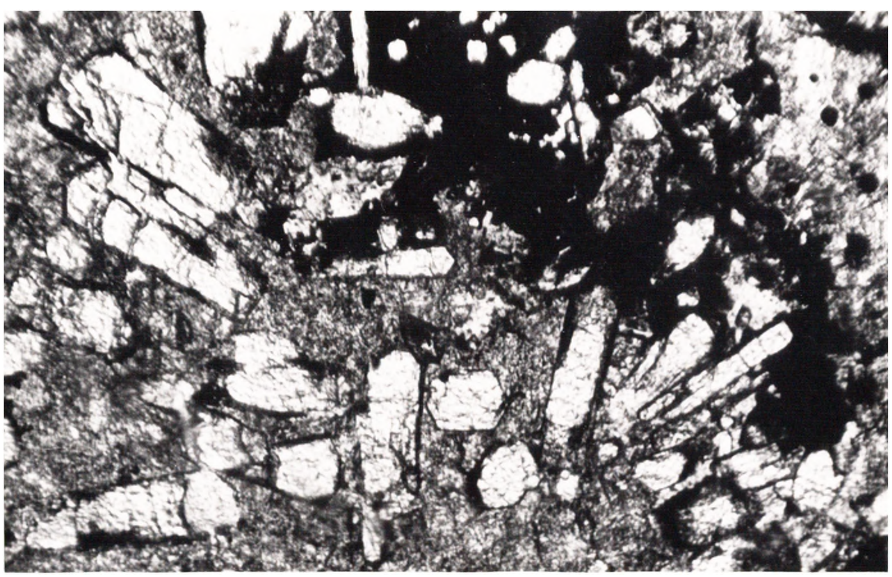


Figure 17b. Sample A-7. Longitudinal sections of apatite. Size of grain up to 2 mm. Location: Calderon Bajo. 50X, plain light.

Sample number: C-9

Locality: Calderon area, lower part (Calderon bajo); Vilcabamba district, Cuzco Department, Peru.

Megascopic description:

Greenish rock composed mainly of garnet, with interstitical opaque minerals and calcite. In places the opaque portion consists clearly of specular hematite.

Microscopic character:

Garnet (85%): Cracked and largely altered shows therefore anomalous anistropism.

Calcite (10%): Interstitial in the garnet mass.

Opaques (5%): The opaques normally line the interstitial spaces between calcite.

Quartz and other minor constituents are occasionally present but almost without exception obscured by yellowish greenish alteration products.

Rock name: Garnetite

Sample number: A-15 (50)

Location: 20 m. SE of Andrianita pit, Vilcabamba district, Cuzco Department, Peru.

Megascopic characters: Medium to fine-grained, darkish mottled massive rock.

Microscopic characters:

I. Phenocrysts:

Augite (25%): Irregular forms, frequently including a fish (Figure 18a) or needle-shaped mineral which is almost isotropic; cleavage rather obscure; size up 2. mm.

Olivine (altered, 15% approximately): Isomatric! grains of a mineral with low relief (Figures 18b and c) ; frequently associated with opaques (probably iron oxide).

II. Matrix (60%): Very fine grained mixture of possible plagioclase, with pyroxene, serpentine, talc, chlorite, and iron oxides.

III. Rock name: Hybrid augite-dunite or olivine-pyroxenite.

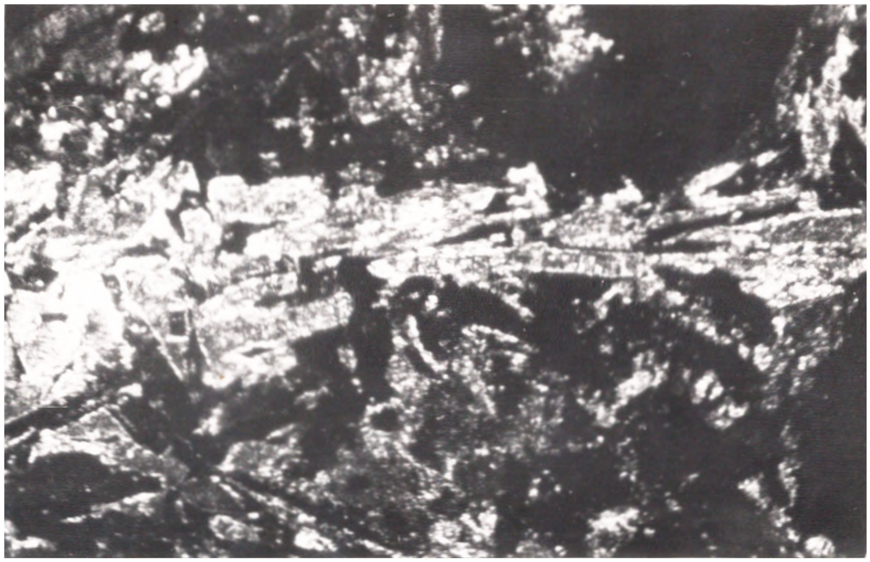


Figure 18a. Sample A-15 (50). Augite; dendritic, sheave-like type (herringbone structure) (compare GANSSER, 1950, p. 230-233). 50X, crossed

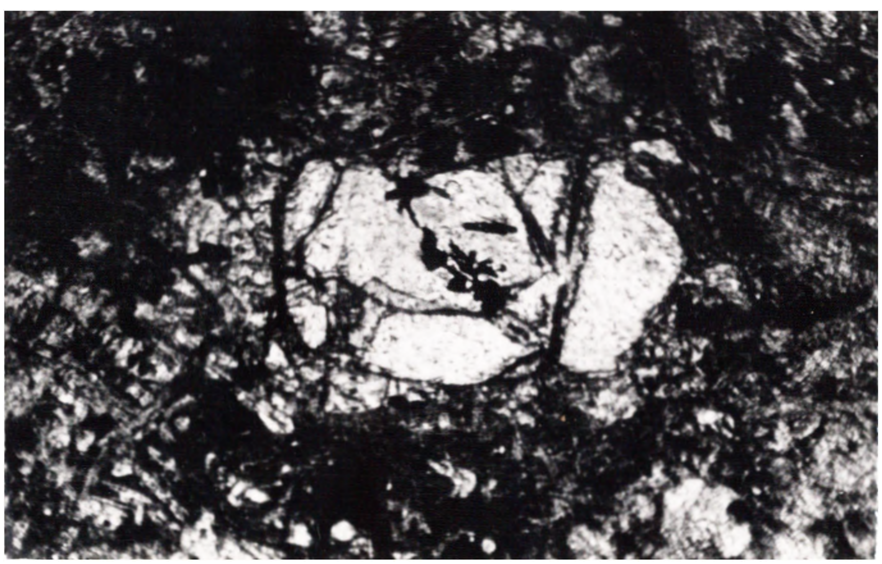


Figure 18b. Sample A-15 (50). Chlorite patch pseudomorphic after olivine. 50X, plain light.

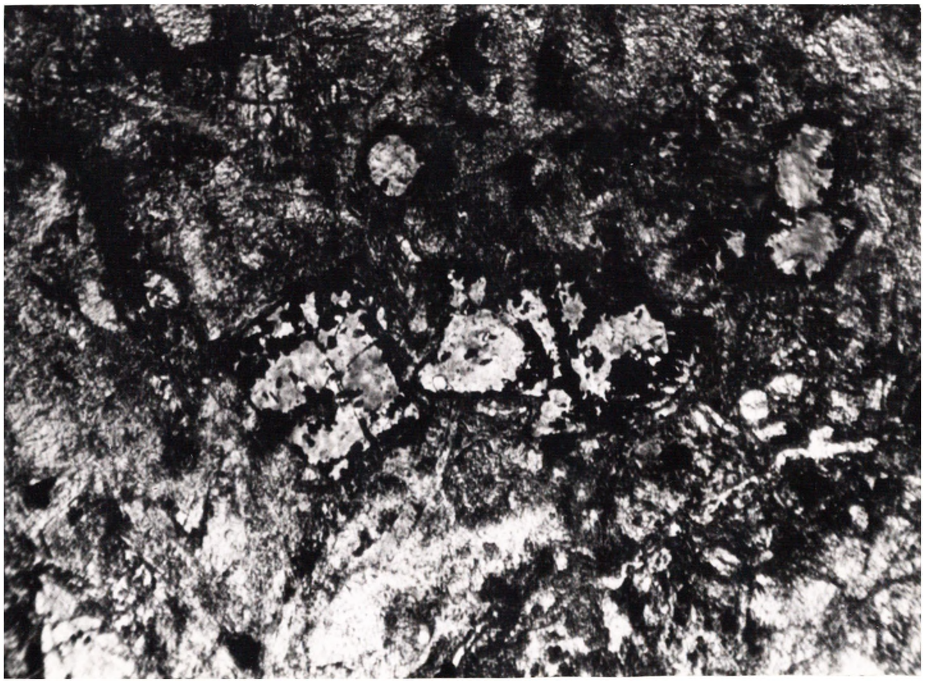


Figure 18c. Sample A-15 (150). The break-down of olivine gives rise to the development of iron-oxide minerals (limonite). 50X, plain light.

Specimen number: A-16

Location: San Marcos dike, near San Marcos pit; Vilcabamba district, Cuzco department, Peru.

Megascopic characters: A fine-grained, grayish to greenish rock. Biotite is abundant and shows some alteration to chlorite.

Microscopic characters:

I. Phenocrysts:

Plagioclase (20%): Andesine (36 An); quite cloudy and saussuritized; size of grains ranging from .3 to 1.5 mm.

Augite (20%): Euhedral crystals on basal and longitudinal section; zoning in some (Figure 19a and b), size 1-2 mm.

Biotite (35%): Largest crystals abundant; section parallel to (001) and (010); associated with zircon; size of grains up to .2 mm.

II. Matrix (not sharply distinguishable to size from phenocrysts):

Main components: The groundmass is composed of small lath-shaped plagioclase crystals, with interstitial quartz biotite, augite crystals; amount included in that of the phenocrysts.

Accessories (15%): Zircon, euhedral, typical form; magnetite, predominantly located along the border of the corroded biotite; few grains of sphene.

III. Patches and "Bubbles": Calcite containing zeolites, talc, serpentine (25%); vesicular in nature, or possibly hybrid inclusions from neighboring limestone (Figure 3).

IV. Rock name: Andesite

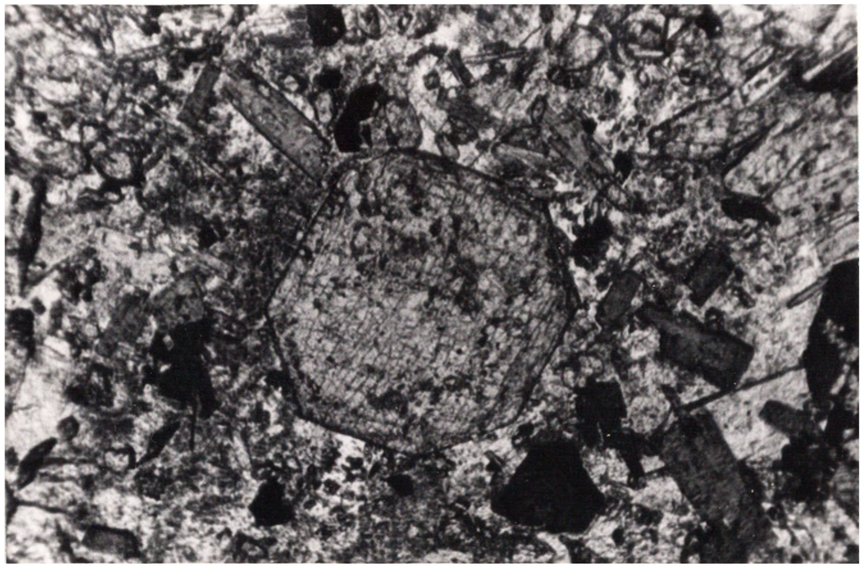


Figure 19a. Sample A-16. Augite normal to the C-axis. Some zoning is noted along the rim. Elongate biotite also is noted in the neighborhood. 50X, plain light.

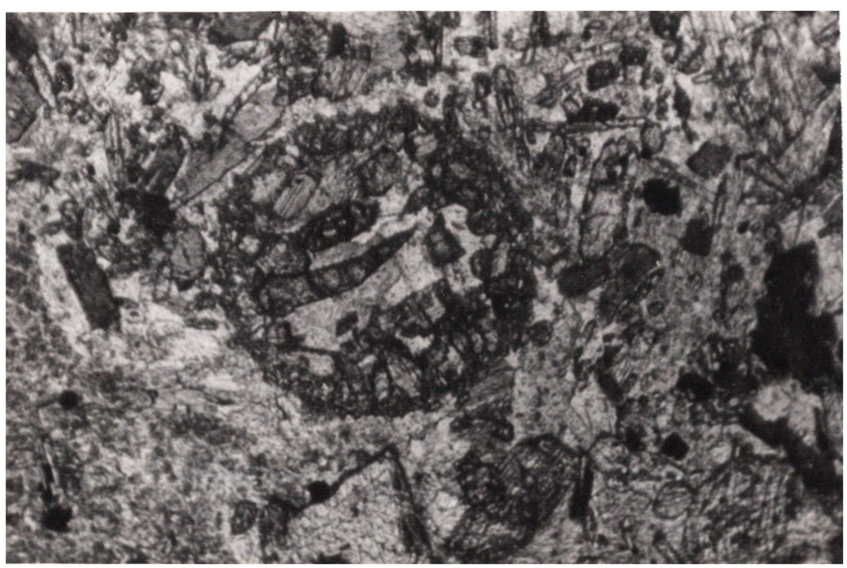


Figure 19b. Sample A-16. Calcite "bubble" containing epidote, serpentine, talc, and zeolites. 50X, plain light.

3. <u>Chemical Analyses</u>

In order that the major rocks of the area could be compared with other petrochemical provinces of Peru, chemical analyses of six important rocks were obtained. The results are found in Table I. The NIGGLI values of all Peruvian rocks are given in Tables II to IV.

The magma types were evaluated and will be discussed in the following paragraphs.

The magma classification of the six rocks analyzed was performed according to the list published by NIGGLI and BURRI (1945, p. 31-36). The comparison of the NIGGLI values with the list led to the following magma types. While this classification is most useful for comparison purposes, one should not infer that each and every single magma type came from an independent and separate magma chamber. It is possible that one magma chamber may have produced various differentiation products, and assimilation may also have produced marked changes in the bulk composition and the trend of crystallization.

<u>Rock 2-A (48)</u> fits well into the class of aplitic-quartz-dioritic magmas (type 1-d-3).

<u>Rock 2-B (49)</u> fits perfectly into the class of granodioritic magmas (type 1-c-1).

Rock 50. (A-15) is the most difficult rock to classify because it apparently contains a large amount of contaminations. This fact is clearly demonstrated by the high content of c which does not permit entering this rock into any normal type of magma. It is closest to the ijolitic (turjaitic to okaitic) type (11-h-5)except for the very high c and the anomalous alk (only 0.65.). It is, on the other hand, also close to the melanogabbroid (ankaratritic type, 11-0-2), again except for the high c and, consequently, low fm. This rock illustrates the need for rock analyses in cases where the mineralogic composition is anomalous and the grain size small.

Rock 51 (M-1) fits two classifications about equally well: it falls between the sommaitec and the monzonitic types (111-f-c and 111-g-1).

Rock 52 (M-2) enters well into the group of theralitic to theralitic-gabbroic magmas (types 11-K-1 and 11-m-2).

Rock 53 (M-3) corresponds to the transition between the syenitic (kamperitic; 111-3-3) and lamprosyenitic (111-i-l) magma type.

The QLM values are claculated according to the simplified rules given by BURRI, NIGGLI 91945, p. 96). The fm-al, alk-al, and the mg-k, and variation diagrams were drawn also according to this publication (p. 30, 61, 62).

The simplified rules used for the QLM diagram are as follows:

I. alk al

$$Q = si - 100 - 1/2\ (fm + c) =$$

$$si - 50 + 1/2\ (al + alk)$$

$$L = 6\ al$$

$$M = 3\ (alk - al) + 3/2\ (fm + c)$$

II. al = (alk + c)

$$Q = si - (50 + 2\ alk - al)$$

$$L = 3\ (al + alk)$$

$$M = 3\ (50 - al)$$

Figure 20

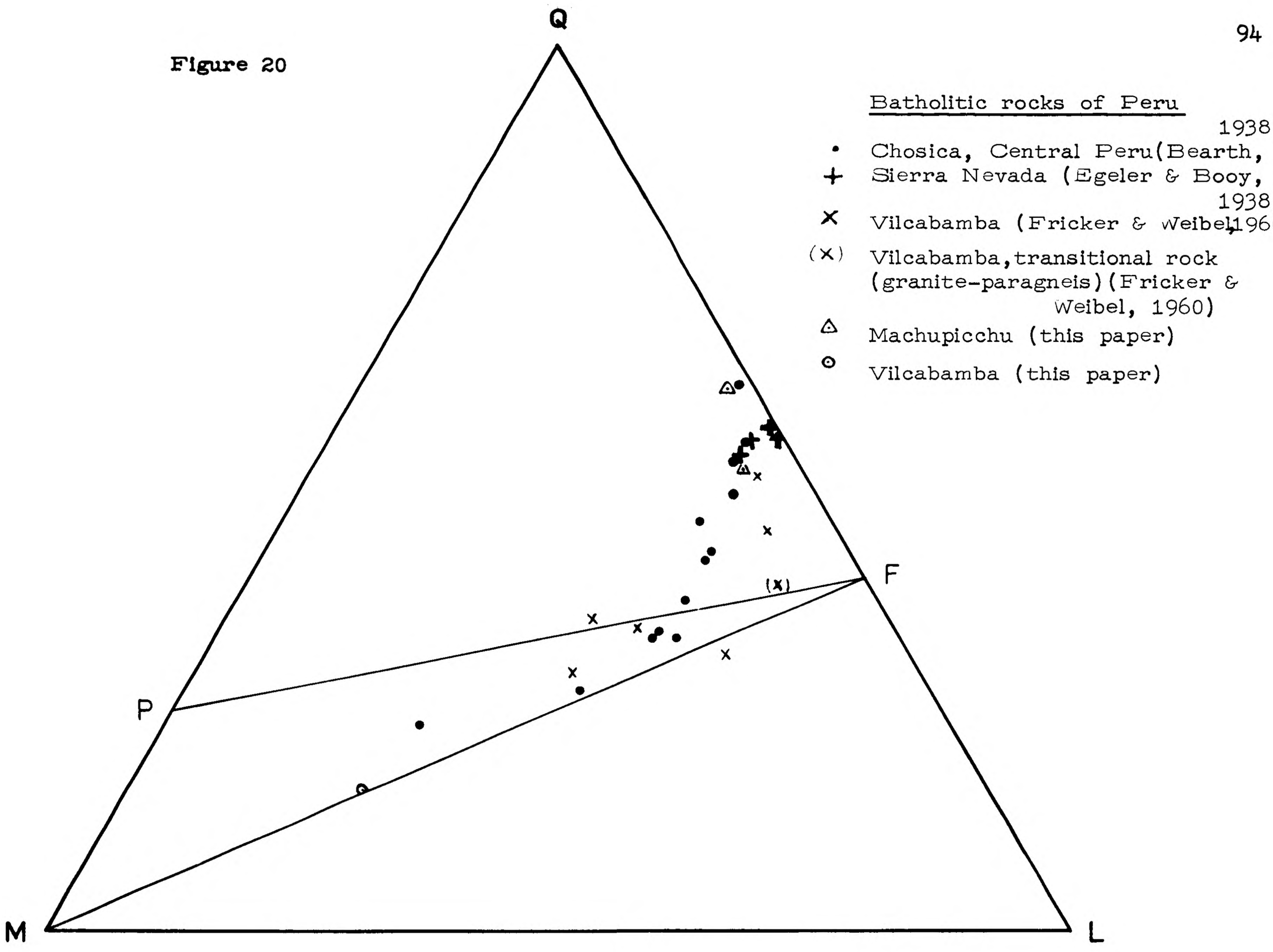
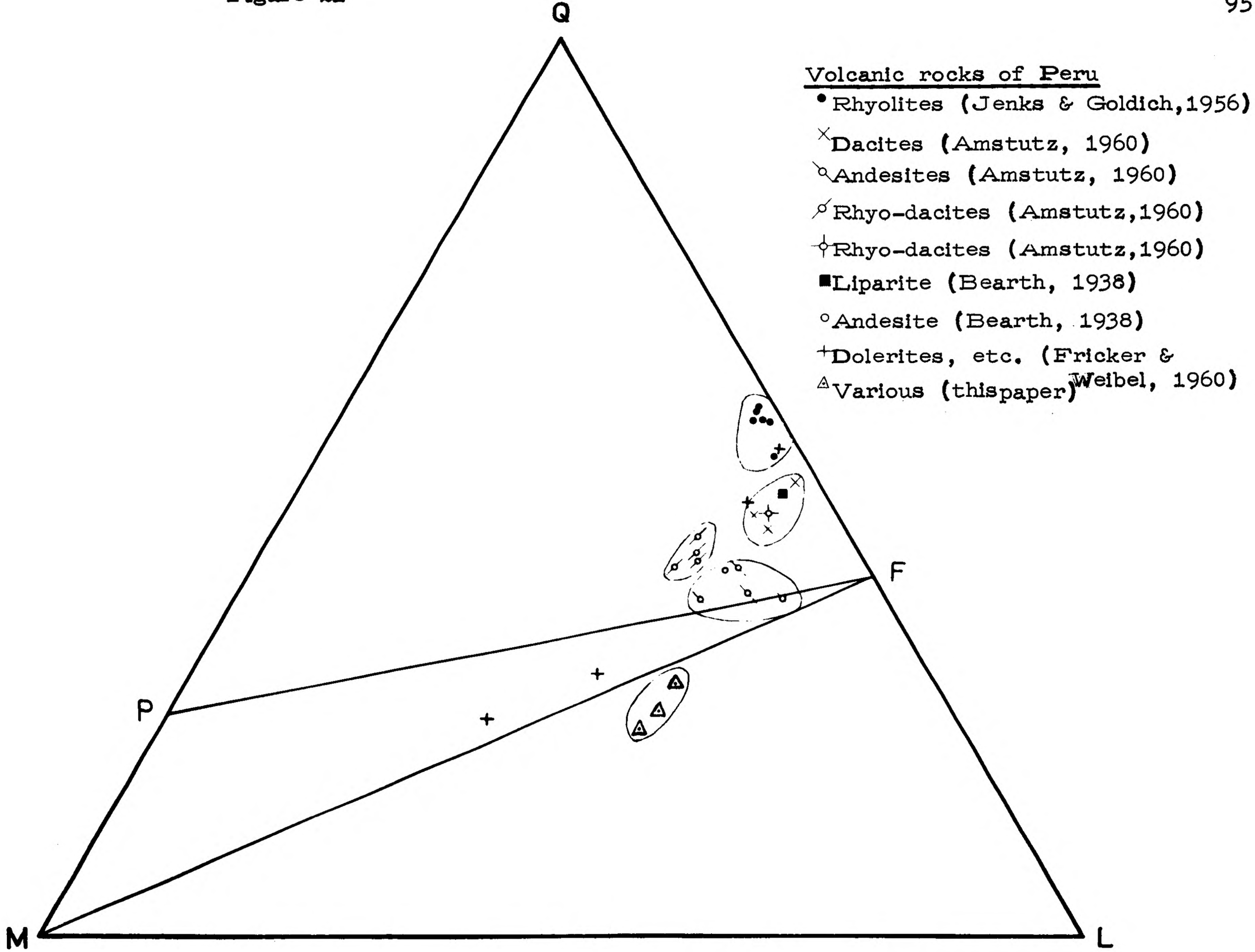

Q
P
F
M
L
Batholitic rocks of Peru
1938
Chosica, Central Peru(Bearth,
Sierra Nevada (Egeler & Booy,
1938
Vilcabamba (Fricker & Weibel, 1960
(x) Vilcabamba, transitional rock (granite-paragneis) (Fricker & Weibel, 1960)
Machupicchu (this paper)
Vilcabamba (this paper)
(x)

Figure 21


Q
F
P
M
L
Volcanic rocks of Peru
Rhyolites (Jenks & Goldich,1956)
Dacites (Amstutz, 1960)
Andesites (Amstutz, 1960)
Rhyo-dacites (Amstutz,1960)
Rhyo-dacites (Amstutz,1960)
Liparite (Bearth, 1938)
Andesite (Bearth, 1938)
Dolerites, etc. (Fricker & Weibel, 1960)
Various (thispaper)

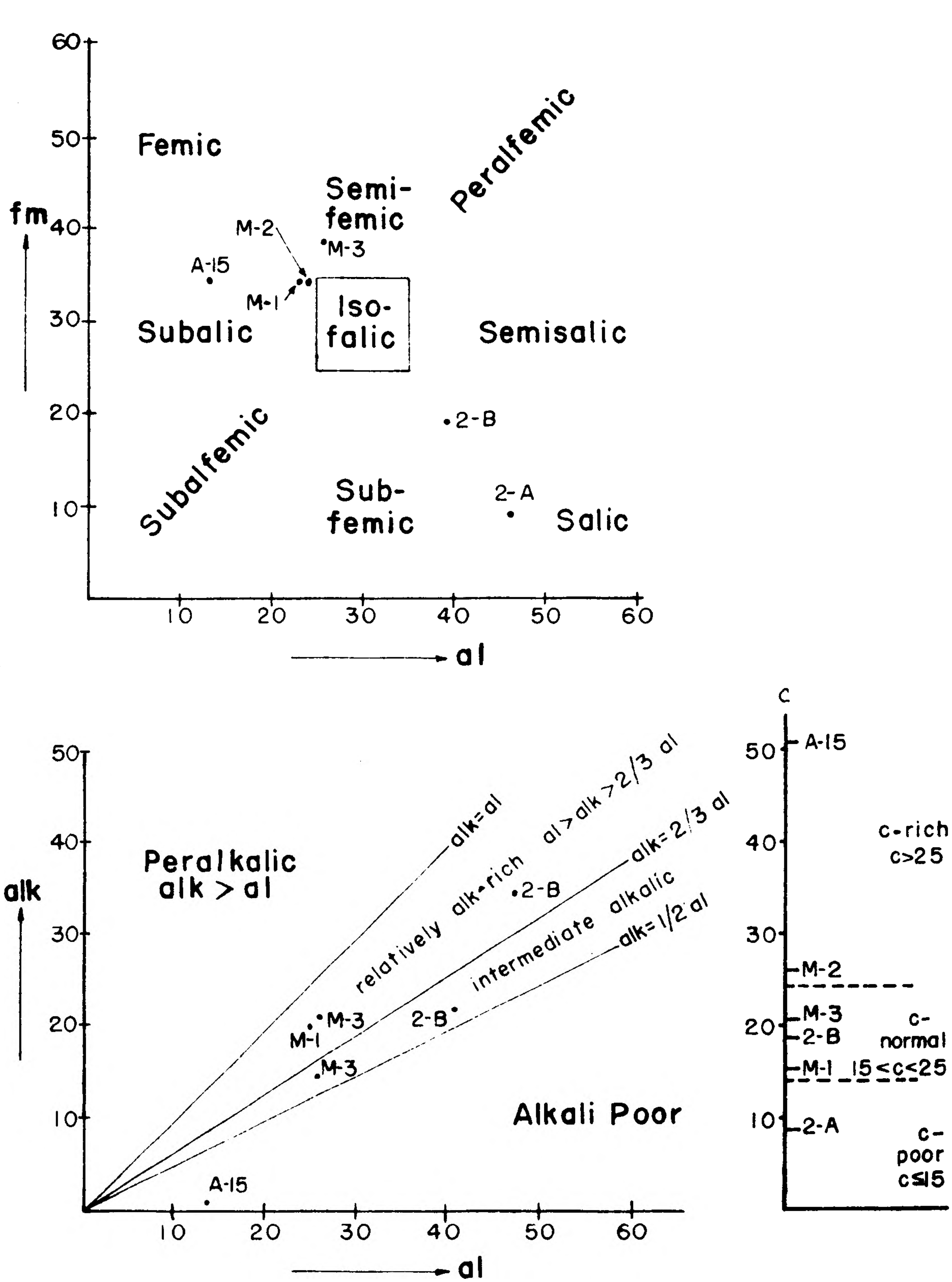


Figure 22 fm-al, alk-al, and c fields with the locations of the new rock analyses

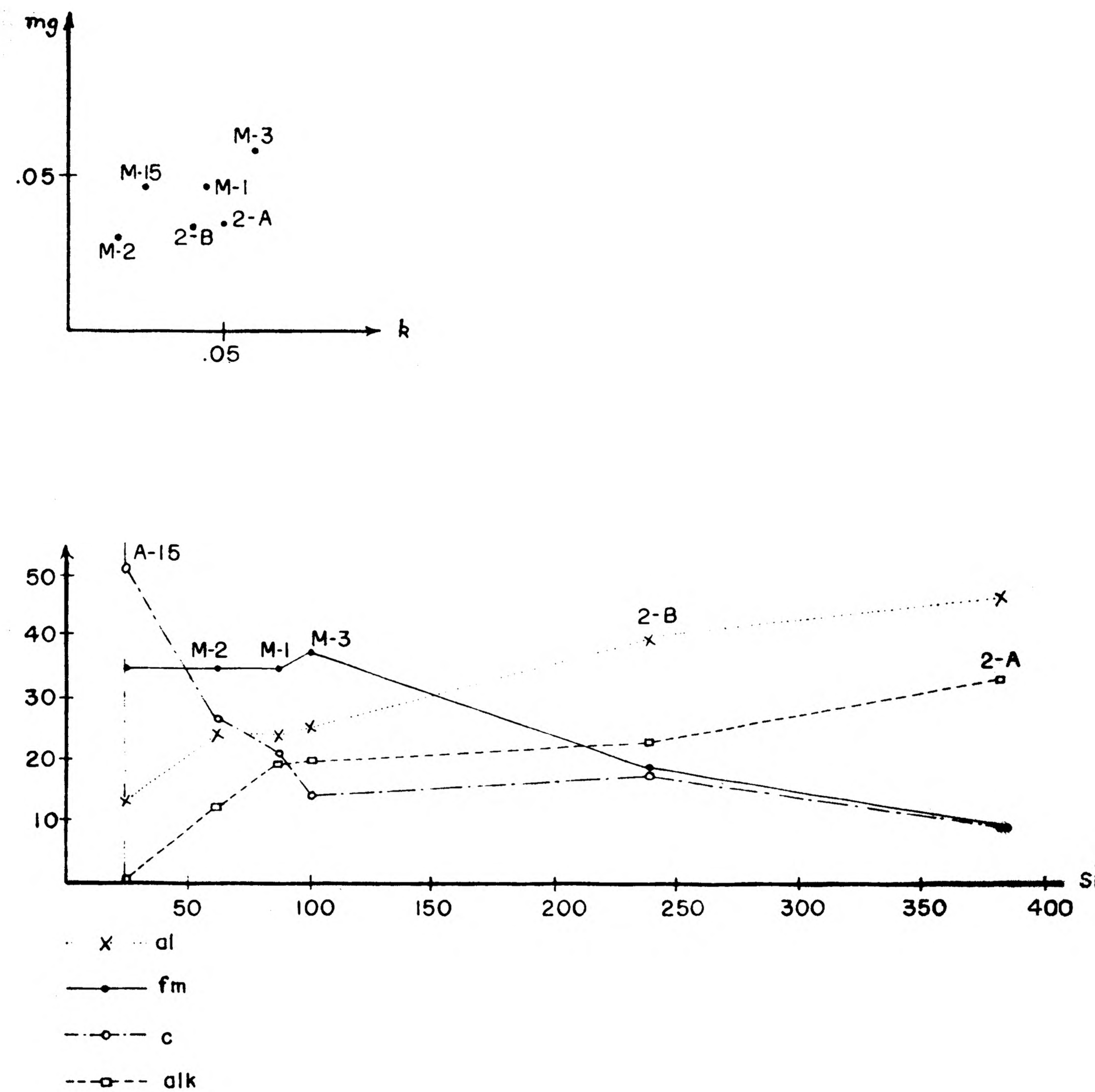


Figure 23 mg-k, and variation diagram of the new rock analysis

TABLE I

New Analyses of Igneous Rocks from Peru, Vilcabamba Area

(after 1960; No. 48-53 this thesis)

	2-A(48)	2-B(49)	A-15(50)	M-1(51)	M-2(52)	M-3(53)
SiO_2	73.7	68.2	38.4	50.8	42.9	52.2
TiO_2	.20	.36	1.1	1.7	1.4	1.6
Al_2O_3	13.7	15.8	12.0	14.5	16.2	14.8
Fe_2O_3	.6	.6	3.0	2.1	2.7	2.9
FeO	1.4	2.7	6.9	4.9	7.5	3.8
MnO	.05	.06	.15	.13	.12	.13
MgO	.8	1.2	7.3	4.5	3.3	5.3
CaO	1.5	4.1	27.2	7.2	10.1	5.1
Na_2O	3.6	3.7	.3	5.1	5.0	3.7
K_2O	3.8	2.6	.1	3.8	1.0	5.9
P_2O_5	.07	.14	.23	1.0	.19	1.0
H_2O	.5	.3	2.4	2.0	3.8	2.6
CO_2				2.0	5.0	.7
	99.9	99.8	99.1	99.7	99.2	99.7

TABLE II

ANALYSES OF INTRUSIVE ROCKS OF PERU

(Up to Rbo)

Author and Year										
Bearth (1938)	1	58.34	206	34	28.5	19.5	18	43.0	43.7	13.3
(all from	2	77.31	527	47	5	7.5	40.5	61.8	39.9	1.3
Central Peru)	3	68.72	325	40	18	15	27	53.2	40.7	6.1
	4	64.40	251	32.5	25.5	19.5	22.5	46.3	40.7	13.0
	5	59.83	202	33	30	19	18	42.0	43.5	14.5
	6	55.57	161	31	32	23.5	13.5	37.5	43.6	18.9
	7	50.06	127	29	25.5	26.5	9	33.6	42.4	24.0
	8	43.59	92	25	39	32.5	3.5	27.3	38.6	34.1
	9	46.12	90	14	58.5	24.5	3	23.6	24.6	51.8
	10	50.93	134	30	32.5	26	11.5	33.1	45.1	21.8
	11	50.17	144	27.5	37	22.5	13	33.6	42.6	23.8
	12	66.72	282	38	19.5	17.5	25	49.4	42.5	8.1
	13	70.54	365	47.5	10	12	31	55.3	40.7	4.0
Egeler and	14	66.97	284.7	41.6	20.4	18.6	19.4	53.3	41.0	5.7
Body (1956)	15	70.66	339.5	44.1	14.1	15.3	26.5	55.0	41.5	3.5
(all from	16	73.10	398.0	48.4	7.5	10.8	33.3	56.9	42.3	0.8
the Cordillera Blanca)	17	71.60	381.5	49.5	8.0	8.9	33.6	55.5	44.2	0.3

Names of the rocks:

1. Quarzdiorite
2. Alkali-granite
3. Horblende-biotite-granite
4. Granodiorite
5. Granodiorite
6. Diorite
7. Uralitegabbro
8. Uralitegabbro
9. Melagabbro
10. Mikrodiorite
11. Lamprophyre
12. Graniteporphyry (Quartz monzonite porphyry)
13. Graniteporphyry
14. Tonalite
15. Granodiorite
16. Leucogranodiorite
17. Granodiorite-porphyry

TABLE III

Analyses of extrusive rocks of Peru

(up to 1960)

Author and Year	No.	SiO_2	si	al	fm	c	alk	Q	L	M
BEARTH	18	68.65	319	43	12	11.5	33.5	49.4	46.4	4.2
(1938)	19	56.18	180	35	25.5	24.5	15	40.9	45.6	13.5
(Central Sierra)										
JENKS	20	70.81	412	48	5.5	13.5	43	53.5	43.8	2.7
and	21	73.03	417	47	7.5	10.5	35	57.3	41.2	1.5
GOLDICH	22	74.06	443	47.5	6	6.5	40	57.4	40.8	1.8
(1956)	23	74.63	465	50	4.5	4.5	41	58.4	39.6	2.0
	24	75.01	473	48	5.5	5.5	41	58.9	39.6	1.5
(average)		74.18	450	48	6	7.5	38.5	58.3	39.6	2.1
AMSTUTZ	25	54.79	237	36.5	17	11.5	35	37.7	52.5	9.8
(1960)	26	57.70	225	34.5	18.5	21,5	25.5	41.0	46.8	12.2
"	27	52.09	204	34.5	22	19	24.5	38.4	48.7	12.9
"	28	50.80	184	30	23	27.5	19.5	37.4	44.7	17.9
(unpublish)	29	63.77	242	29	20	24	27	41.9	42.3	15.8
"	30	62.35	225	27	26	23.5	23.5	41.2	40.4	18.4
"	31	63.40	247	31	23	21	25	44.5	40.9	14.6
"	32	63.60	242	30	22	22.5	25.5	42.9	41.7	15.4
"	33	63.57	298	38	18	7.5	36.5	45.1	47.3	7.6
"	34	68.52	378	48	6.5	1.5	44	50.5	47.1	2.4
"	35	65.35	305	40.5	21.5	3	35	46.9	45.6	7.5
"	36	69.87	318	39.5	9.5	14	37	47.1	46.6	6.3

Rock name and/or locality:

18 Dacite (plagioeiparit), between Pongo and Ampi.
19 Andesite, Laguna Karpa.
20 - 24 rhyolitic volcanics of Southern Peru.
25 Andesite, Antachajra (ore).
26 Andesite, Caprichosa (fresh).
27 Andesite, Caprichosa (ore).
28 Andesite, Caprichosa (ore).
29-32 Volcan Tutupaca, South Peru
33-35 Mine Julcani
36 Bosque de Piedras, Departam. de Junin, Central Peru. (rhyo-dacite).

TABLE IV

Synopsis of all Rock Analyses From The Vilcabamba Area, Peru

Author & Year	No.	SiO_2	si	al	fm	c	alk	Q	L	M
Fricker & Weibel (1960)	37(151)	73.0	422	47	5	5	43	54	44	2
	38(3853)	66.9	292	39	18	8	35	45	48	7
	39(184)	69.6	343	42	17	5	36	51	44	5
	40(214)	55.7	177	31	33	14	22	31	51	18
	41(96)	61.0	227	38	23	9	30	39	52	9
	42(101)	52.9	144	23	44	22	11	35	36	29
	43(275)	50.8	140	27	43	19	11	34	41	25
	44(356)	50.4	127	21	46	22	11	29	37	34
	45(66)	47.6	12	23	44	23	10	29	39	32
	46(130)	43.0	97	17	47	30	6	24	31	45
	47(249)	67.2	305	37	21	9	33	48	44	8
Aguilar (This Thesis)	48(2-A)	73.7	424	47	10	9	34	61	36	3
	49(2-B)	68.2	291	40	19	19	23	52	42	6
	50(A-15)	38.4	69	13	34	52	1	16	23	61
	51(M-1)	50.8	141	24	36	21	21	25	47	28
	52(M-2)	42.9	110	24	34	28	14	23	46	31
	53(M-3)	52.2	150	25	38	16	21	28	47	25

Names of the Rocks:

37(151)	Quartz porphyry
38(353)	Granodiorite
39(184)	Granodiorite
40(214)	Basic grandiorite
41(96)	Paragneis to granite (transition)
42(101)	Tonalite
43(275)	Quartz diorite
44(356)	Gabbro-diorite
45(66)	Dolerite (with titaniferous augite)
46(130)	Dolerite (with titaniferous augite)
47(249)	Quartz porphyrite
48(2-A)	Quartzdiorite
49(2-B)	Granodiorite
50(A-15)	Hybrid olivine-pyroxenite
51(M-1)	Trachy-andesite
52(M-2)	Lamprophyre
53(M-3)	Keratophyre to albite-lamprophyre

C. STRUCTURE

Two main types of structures occur in the thesis area.

1. Faults.

The major faults are: (1) Negrillas, and (2) Calderon fault, as can be noted on the geologic map. Both of these faults strike E-W, the Negrillas fault dips 70-80° to the south, and the Calderon fault dips almost vertical, or in some places steeply inclined to the south.

The Negrillas reverse fault can be followed on the surface for approximately three kilometers (Figure 11, and the structural map in the Appendix), i.e. from the rio Cayari to quebrada Chalcha. This fault shows a slight increase in radioactivity near Negrillas lake. At this location the fault cuts the limestone formation, which, as previously mentioned, contains erratic lenses or patches of pitchblende. No primary uranium minerals are found associated with the fault. Therefore the radioactivity may be due to secondary deposition from solutions containing uranium derived from the limestone.

The Calderon fault which is located about 1 km. north of the Negrillas fault, extends for about 1/2 km., and trends E-W (Figure 8). The fault appears to have originated during the volcanic activity in this area. This fault places metamorphosed limestone in contact with the volcanic rocks.

Neither the Negrillas nor Calderon fault contains mineralization. However, some of the fractures associated with the Calderon fault contain mineralization.

2. Fractures

Closely associated with the Calderon fault are two sets of fractures found in the adjacent metamorphosed limestone; one set is parallel, and the other angular. The parallel fractures trend in the same E-W direction as the Calderon fault and are vertical or steeply inclined to the south. They control the location of the major cliffs in the area (see structural map in the Appendix) and contain no ore mineralization. The fracture planes show no evidence of movement. Based on their field occurrence and characteristics, they are classified as sympathetic fractures.

Another set of fractures trending N 15-25° E shows an angle with the Calderon fault. An exception to the above generalization is the Aurora fracture which strikes N 50° E and dips approximately 75° NW.

Angles of inclination to the Calderon fault vary from 45-80°. Many of the inclined fractures contain abundant pyrite and some contain scattered distribution of ore minerals. The Aurora fracture exhibits the strongest pyrite mineralization.

Four un-named fractures east of Calderon prospect show slight mineralization and were worked for their ore values probably during the 16th and 17th Centuries.

V. ORE DEPOSITS

This chapter includes a description of the individual occurrences of uranium minerals in the two adjacent areas, Huamanapi and Calderon. In the Huamanapi area mineralization of copper-uranium and nickel minerals occurs in lenticular arrangements within limestone host rock. San Marcos and Adrianita area the major prospects within this first area. In addition there are some other smaller prospects which will not be mentioned specifically. In Calderon area copper - uranium - nickel mineralization occurs mainly as fissure fillings and the host rock is skarn. The Aurora and Calderon fractures are described as typical features of this second area.

A. HUAMANAPI AREA

The ore mineralization in the area of Huamanapi in which the San Marcos prospect lies, occurs as lenses of various dimensions, both in the horizontal and vertical views. The lenticular character of the deposits is the main feature in that area. These bodies occur in carbonate rocks of the Copacabana group. The limestone rocks are locally altered to silicate minerals in and near the ore deposits.

1. San Marcos Prospect

The San Marcos prospect is a lens which trends roughly E-W and plunges 80° to the south. It is about 10 m. long and 1 m. wide. Although the ends of the lens have not been found, it is most probable that it terminates not far from the outcrops, because the habit of the ore mineralization in this locality is short lense-like bodies. For the same reason it is also probable that the lens does not extend far below the surface.

McKINSTRY (1955, p. 207) in describing pipes and mantos states:

> "Orebodies of roughly circular or oval section are commonly described as pipes or chimneys if they are vertical or steeply inclined. If they are more nearly horizontal and, particularly, if their long axes lies in the plane of bedding of the inclosing rock they are often referred to as mantos."

He continued in a footnote:

> "Manto means blanket and should, literally speaking, be reserved for tabular bedded replacement. But in Santa Eulalia and other Mexican occurrences it is used for horizontal tubes along bedding planes in contradistinction to the steep chimneys, a usage that has spread in the literature, e.g., to Gilman, Colorado, and even to Derbyshire. Rather than combat this extension or distortion of the term, it may be simplest when writing in English to retain it for horizontal pipes and revert to "blanket" for tabular bedded replacements, as long used in Leadville and elsewhere."

LOCKE (1926, p. 446) states:

> "solutions, whatever their original path may have been, can dissolve out a chamber which then begins to cave".

These statements describe the mode of occurrence and manner of formation of the lens at San Marcos and of others in the Huamanapi area, except for a local limestone breccia 150 m. below San Marcos pit. This breccia has a trend and dips similar to that of the San Marcos pit. The limestone breccia is cemented with hematite and sporadically contains chalcopyrite and weakly disseminated pitchblende. Exploration to date has not shown pipes, chimneys or mantos of the size described in the literature for some other mining districts.

a. <u>Host Rock and Description of Prospect.</u> The host rocks for the introduced ore minerals are a comparatively thick series of a relatively thin bedded limestone, metamorphosed to marble. Broadly speaking, the calcareous formation underwent greater alteration than sandstone. A wide range of variable zoning of alteration characterized by the development of such silicates as garnet, epidote, serpentine, etc. is seen.

The gangue of the ore is coarse-grained calcite and dolomite. Locally the gangue is pinkish due to a high content of hematite. A lesser amount of silica occurs at 10 m. above the San Marcos pit. Quartz and hematite are well exposed. These trend in the same direction as the San Marcos mineralization. It is interesting to note that 5 to 7 m. from the footwall of the San Marcos pit, the limestone becomes cherty.

b. <u>Ore Minerals and Pyrite.</u> In order of abundance, the ore minerals and pyrite include pyrite, tetrahedrite, bornite, niccolite, pitchblende or uraninite and sulfoarsenides of nickel and cobalt. The alteration of the copper sulfide minerals in some places has reached an advance state.

The ore minerals have a spotty distribution within the calcite gangue. Only the pyrite appears to be persistent.

While chalcopyrite and bornite appear to be enclosed in calcareous gangue with a higher content of silica, tetrahedrite, pitchblende, and Ni-Co arsenides tend to be present in a pure calcite gangue. This, however, may not always be the rule.

c. Ore Microscopy. Before considering the minerals studied under the microscope the author wishes to quote some important statements in regards to the definition of pitchblende and uraninite.

Pitchblende: The name pitchblende is used in this thesis instead of uraninite because the appearance of this uranium mineral is amorphous instead of isometric. This is based on the terminology of Report RMO-563 of the U.S. Atomic Energy Commission by GEORGE (1949, p. 31).

E. W. HEINRICH (1958, p. 26) under the title "Uraninite and pitchblende", gives the following definition:

"Composition ideally UO_2 U = 46.5 to 88.2%. Normally U^4 is oxidized to U^6 to a varying extent. As the U^4 ion is replaced by the smaller U^6 ion, extra O ions enter to occupy interstitial positions."

HEINRICH (1958, p. 26) mentions that WASSERSTEIN has suggested a threefold classification of uraninite:

- uraninite - U_4O_7 (Oxygen deficient)

- uraninite - UO_2, uraninite in the strict sense

- uraninite - U_3O_7 (Oxygen in excess), pitchblende in the strict sense.

FRONDEL (1958, p. 12) states:

> "Two names, uraninite and pitchblende, are in common use for this mineral. Uraninite is the correct name for the species as a whole, including all varieties. The name pitchblende is commonly used to designate a more or less sharply defined variety of uraninite. Pitchblende occurs chiefly in hydrothermal metalliferous veins. It forms micro-crystalline masses that often show concentric banding and have a botryoidal or rounded surface when developed as a crust."

Identification of the ore minerals of the Vilcabamba Copper - Uranium ores were based chiefly on studies of polished sections with the reflecting microscope. They revealed the presence of the following ore minerals (description sheets and microphotographs follow at the end of this chapter):

Sample number: B-1

Bornite
Chalcopyrite
Tetrahedrite
Pyrite

Sample number: B-2

Tetrahedrite
Chalcopyrite
Pyrite
Safflorite
Rammelsbergite
Pitchblende (little)
Bravolite (?)
Mineral X

Sample number: B-3

Niccolite
Gersdorffite or Ullmannite
Rammelsbergite
Pitchblende

Sample number: B-4

Bornite
Chalcopyrite
Covellite
Tetrahedrite

Sample number: B-1

Locality: San Marcos prospect.

Megascopic description: Bornite and chalcopyrite are the main copper sulfides and occur as patches in siliceous or perhaps silicified limestone.

Microscopic character:

Bornite (70%): Occurs in massive patches and occasionally shows a pitted surface and a beginning limonitic alteration. One portion of the sample contains almost only bornite, whereas another part contains mostly chalcopyrite. Bornite and chalcopyrite are intergrown in between these two portions. Bornite frequently contains spots of tetrahedrite. Whereas in sample B-4, covellite is common, in this sample it is present only in traces.

Chalcopyrite (25%): Alone or, in a transition zone, intergrown with bornite; this intergrowth is coarse and simple, the boundaries more convex for chalcopyrite than for bornite.

Tetrahedrite (5%): Shows tendency to be intergown with bornite and only rarely with chalcopyrite; this intergowth is very lacy; tetrahedrite contains numerous small whitish spots of a white mineral. The size is so small that their nature cannot be determined with certainty (triangles, rings, spots, or wirelike stringers, of about 2 - 10 micron). However, the reflectivity is so high and the similarity with silver inclusions in tetrahedrite as described by RAMDOHR (1960) is so perfect (p. 304, Figure 281 and descriptions), that we are most probably dealing with native silver skeletons (compare the Ag-skeletons of Sample C-6).

Pyrite (tr.): Occurs in traces or isolated grains.

Cubanite (? tr.): Spots in bornite; strongly anisotropic.

Sample number: B-2

Locality: San Marcos prospect

Megascopic character: Hand specimen shows gray color; tetrahedrite is the predominant mineral.

Microscopic character:

Tetrahedrite (80%): Widespread throughout the sample; occurs intergrown with chalcopyrite and occasionally with pyrite and bornite. Average grain size may vary (from spots of 50 micron to patches of 2mm.).

Chalcopyrite (18%): Intergrown with tetrahedrite in which it forms spots, irregular patches or stringers; shows either smooth fresh or cracked surface; in fewer cases chalcopyrite is intergrown with pyrite.

Pyrite (1%): Isolated spots or grains mostly in the gangue, but also in the sulfides.

Bravoite - Villamaninite (?): In places as a whitish-lilac-pinkish zone around pyrite and often around pyrite-chalcopyrite. The reflectivity is about 40% under oil; it is isotropic and therefore could also be a mineral of the linnaeite group; however, its frequent zoned intergrowth with pyrite suggest that a structural relationship with pyrite exists.

Safflorite (1%); Possibly with traces of rammelsbergite and loellingite): Rosettes of four intergrown crystals (similar to the figure of Sample C-6).

Each one shows narrow outer zone. The color varies in oil from pinkish white to yellowish white. Along the zone border there is occasionally some tetrahedrite.

Mineral X: Highly anisotropic, brownish-pinkish, associated with tetrahedrite and chalcopyrite. Color and hardness of this mineral are the same as that of bornite, but it is sharply anisotropic, like cubanite. It is always intergrown with chalcopyrite. It may therefore be a new mineral, close in composition to chalcopyrite, bornite, or cubanite.

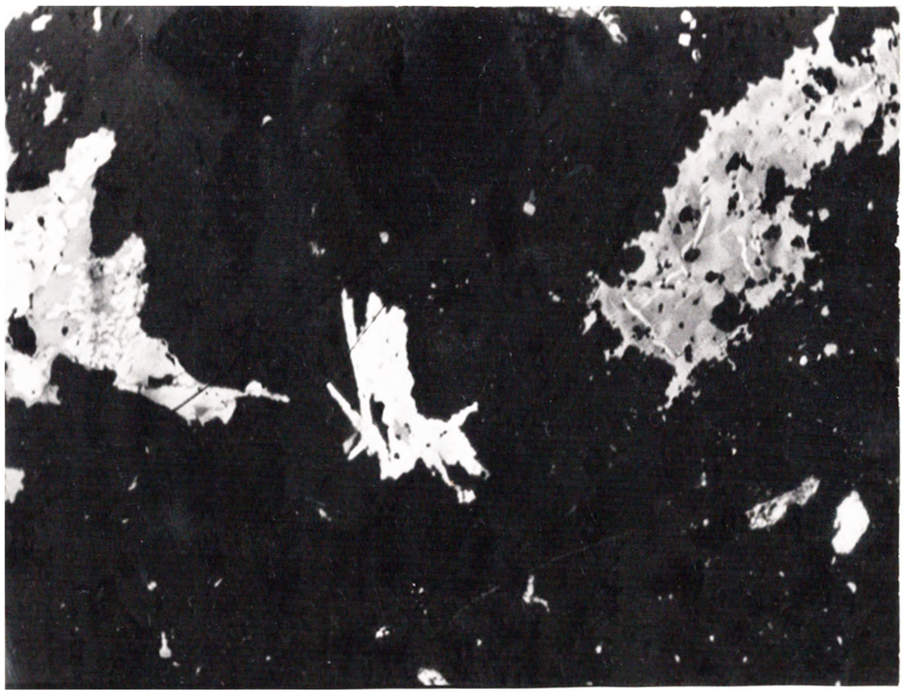


Figure 24. Sample B-2, San Marcos pit. Cobaltite in the center exhibits an acicular form; it is frequently found in needle-like clusters. On both sides are patches with chalcopyrite (white), tetrahedrite (light gray) and a few patches of cubanite (?) (medium grey, in the cluster to the right). 150X.

Sample number: B-3

Locality: San Marcos

Megascopic description: Veinlet of niccolite in altered limestone. The niccolite is light pink to brownish and occupies an irregular tabular space in the wall rock, within this space there appears to be niccolite only. Along the rim of niccolite some patches of probable annabergite occurs.

Microscopic character:

Niccolite (83%)*: Almost entirely homogeneous mass. intergrown in an irregular pattern with rammels=bergite; the latter occurs mainly along the rim of the niccolite mass.

Rammelsbergite (10%): Occurs intergrown with niccolite along grain boundaries and along the rim of the niccolite mass.

Gersdorffite or Ullmannite (5%): Intimately intergrown with Rammelsbergite; almost always within grains of this latter mineral.

Pitchblende (2%): Occurs occasionally as ribbon between rammelsbergite and gangue.

---

*Percentage in all cases refers to the amount of ore minerals only in the sample.

Sample number: B-4

Locality: San Marcos prospect

Megascopic description: Chalcopyrite and bornite are the most abundant sulfides, which seem to display a roughly banded distribution. The gangue is mainly calcite and quartz; limonite and malachite produce heavy stains on the sample.

Microscopic character:

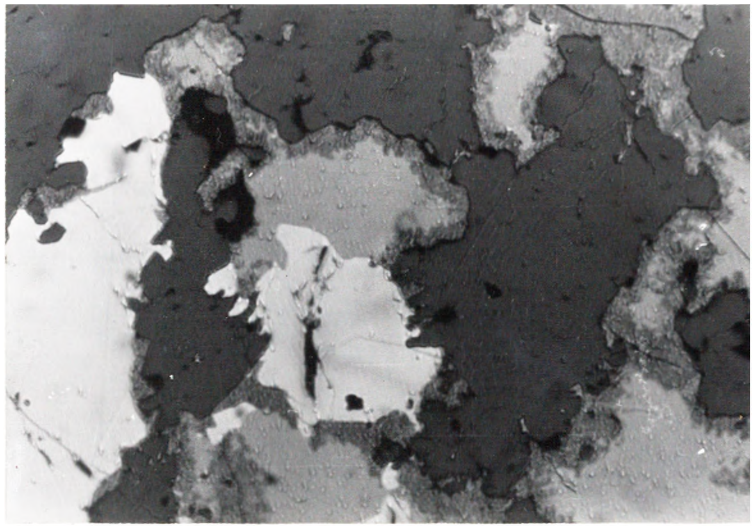
Bornite (50%): Characteristic pink; shows weak anisotropism; almost always rimmed or veined by covellite (Figures 25a and b). Occasionally bornite is also rimmed by a narrow ribbon of chalcopyrite; occasionally chalcopyrite also penetrates the bornite along cleavage plains and grain boundaries; rarely bornite is intergrown with tetrahedrite.

Chalcopyrite (33%): Moderate anisotropism; occurs intergrown with bornite in coarse textures, but also in the more specific way mentioned above; less frequently it is intergrown with tetrahedrite and covellite; occurs abundantly in bornite but only rarely in chalcopyrite (Figure 25a and b); this is remarkable, since covellite may occur alongside both minerals.

Covellite (10%): Appears to replace bornite frequently as supergene mineral from its grain boundaries and cleavage planes; it forms rosettes or mosaics along these lines. Rarely, if ever, covellite replaces chalcopyrite.

Tetrahedrite (5%): Usually as patches inside and as spots along the chalcopyrite and bornite masses.

Pitchblende (±1%): Trace along one boundary of the sulfide mass.



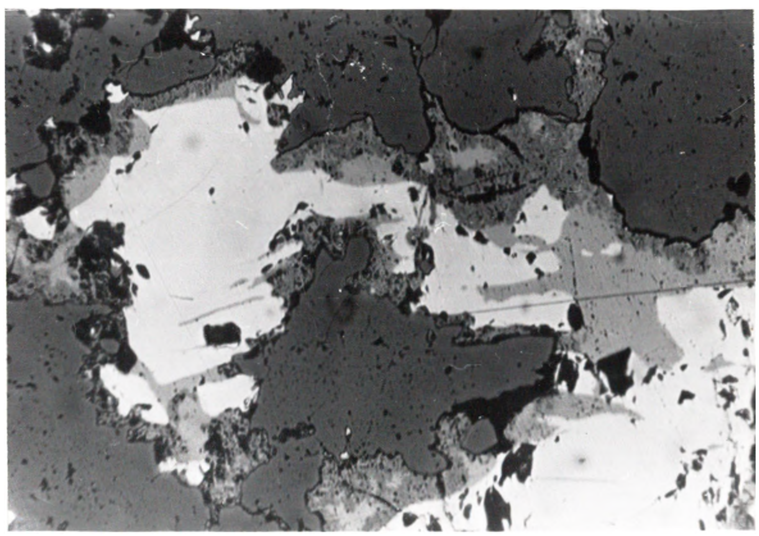


Figure 25a and b. Sample B-4, San Marcos prospect. Bornite (medium light gray) rimmed by covellite (medium dark gray) but not replacing chalcopyrite (light gray); dark gray is calcareous gangue; holes are black. 150 X.

2. <u>Adrianita Prospect</u>

a. <u>Host Rock</u>. In general, at the Adrianita prospect, the host rock has the same character as in San Marcos. It consists of fresh limestones. The gangue consists of pink and white calcite and may be derived from the host rock or introduced.

b. <u>Description of Prospect.</u> The general trend of the lense-like ore zone at the Adrianita prospect is roughly N-S, or almost at right angles to the one at San Marcos. The mineralized zone seems to follow a tension or gash-like fracture. The outcrop length is about 30 m. and the width vanes from 10-40 cms.

GABELMAN (Second visit to Vilcabamba area, department of Cuzco, Peru 1958, p. 2) states:

> "Mineralization is strongest in large joints which constitute the only apparent feeders, but it has spread manto-fashion into the limestone...."

Whether the mineralization has been spread out as in mantos or in lenses, which are common occurrences in Peru and in Mexico, the mode of formation is the same. The relative geometric position depends mainly on the physical-chemical condition of the host rock and on the local structural control. Strictly speaking, mantos have not been found in Huamanapi though they could be expected to occur anywhere within this area. On the other hand, the mineralization at

Calderon and Minasmayo seems to be controlled by tension fractures. From the general setting it could be concluded that mineralization south of the Huamanapi ridge occurs in lense-like bodies and it may occur in manto-fashion. However, to the north of the Huamanapi ridge clear fracture sets are the loci of mineral deposits. This also includes Minasmayo which is located further north of Huamanapi ridge.

Although the amount of pitchblende contained in the spotty clacite is small, the predominant ore mineral is pitchblende. This has a very irregular distribution even within the calcite. Chalcopyrite is nowhere present in abundance, whereas galena occurs disseminated as isolated grains.

Secondary ore minerals derived from niccolite and pitchblende are extremely rare. Neither detrital accumulation nor gossan can be accumulated in an area with slopes of approximately 42° together with frequent rainy seasons. These factors result in the rapid erosion of all incipient weathering products.

c. Ore Microscopy. The study of polished sections from Adrianita prospect reveals the following ore minerals.

Sample number: A-1

Pitchblende (predominant
Chalcopyrite
Galena

Sample number: A-2

Pitchblende (predominant)
Chalcopyrite
Sphalerite
Pyrite

Sample number: A-3

Pitchblende (predominant)
White mineral (radiogenic lead?)
Chalcopyrite

Specimen number: A-1

Location: Pit, Adrianita prospect.

Megascopic character: Pitchblende in discontinuous spots, galena grains scattered in the gangue.

Microscopic character:

Pitchblende (97%): Occurs in reniform to botryoidal masses (Figure 26). Some occur in massive, textureless nodules.

Chalcopyrite (1%): Practically negligible; some occur as submicroscopic specks in gangue.

Tetrahedrite (1%): In disseminated spots in the gangue, often with galena.

Galena: (1%) As isolated spot in the gangue. Tetrahedrite intergrown with galena in simple locking type in some of these spots.

Gangue: Carbonates and probably secondary uranium minerals such as metatorbernite(?).

Specimen number: A-2

Location: Pit, Adrianita prospect.

Megascopic character: Gray hand specimen, composed mainly of pitchblende. Bands of pinkish calcite transect the pitchblende.

Microscopic character:

Pitchblende (98%): Occurs as massive botryoidal, spherulitic forms; ring or cellular shapes are also widespread; thin layers and crusts, although present, are less common (Figure 26). Essentially this sample shows the same structure as sample A-3.

Chalcopyrite and sphalerite (2%): As blebs in the gangue. Pitchblende is not intergrown with chalcopyrite and sphalerite.

Pyrite (tr.): Very occasional traces.

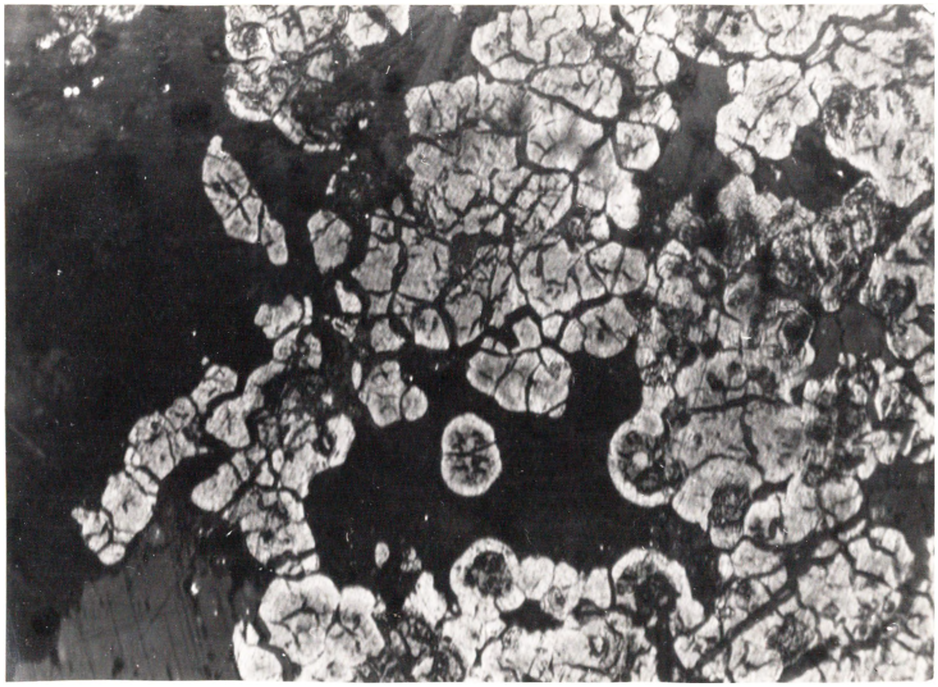


Figure 26. Sample A-2, Adrianita prospect. Botryoidal pitchblende showing low reflectivity and an irregular relief low, probably due to incipients alteration; oil immersion, 500 X.

Specimen number: A-3

Locality: Pit, Adrianita Prospect

Megascopic description: Pitchblende, in a network texture; small spots of annabergite bordering pitchblende, but also occurring in the calcite gangue.

Microscopic character:

Pitchblende (98%): Almost the only ore mineral in this sample. Occurs in a variety of forms, which will be described as distinct types, although they show gradations.

1. Botryoidal forms: Botryoidal forms are exhibited by much of the pitchblende as large mammillary and concentric masses (Figure 27b). It shows numerous cracks and is cemented by calcite or by radiogenic lead. The latter also forms the matrix outside the uraninite.

2. Spherulitic forms: Distributed usually at the border of the massive pitchblende; shows concentric cracks.

3. Ring-like texture: Type 1 or 2 may align into ring-like patterns. They vary in diameter usually from 2 to 4mm. In other cases they show coalescence to form irregular circular patterns. (see Figure 27c)

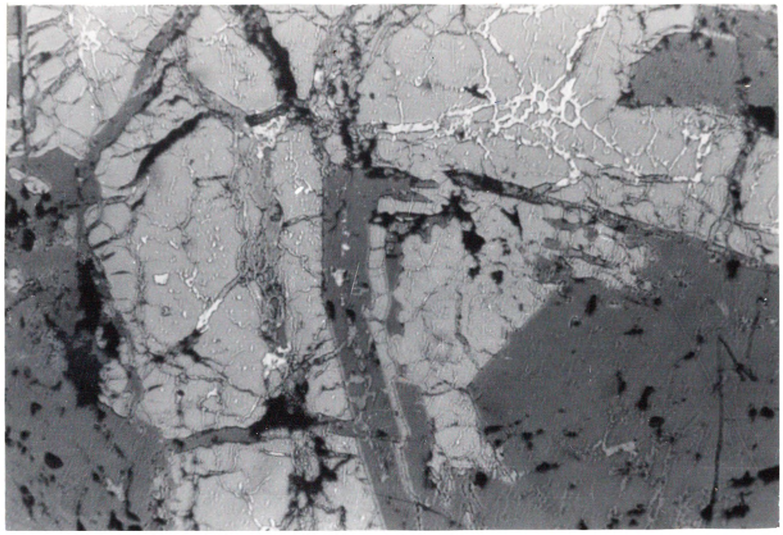


Figure 27a. Sample A-3, Adrianita prospect. Calcite (dark gray) intergrown along its growth planes with pitchblende (light gray). Radiogenic lead in cracks. 150X.

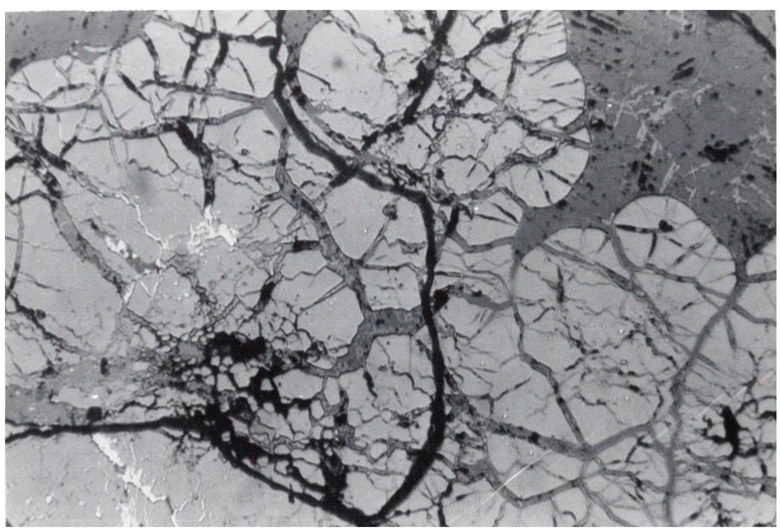


Figure 2 7b. Sample A-3, Adrianita prospect. Polished section showing typical botryoidal structure of pitchblende. Fine veinlets of radiogenic lead in the cracks of pitchblende. 150X.

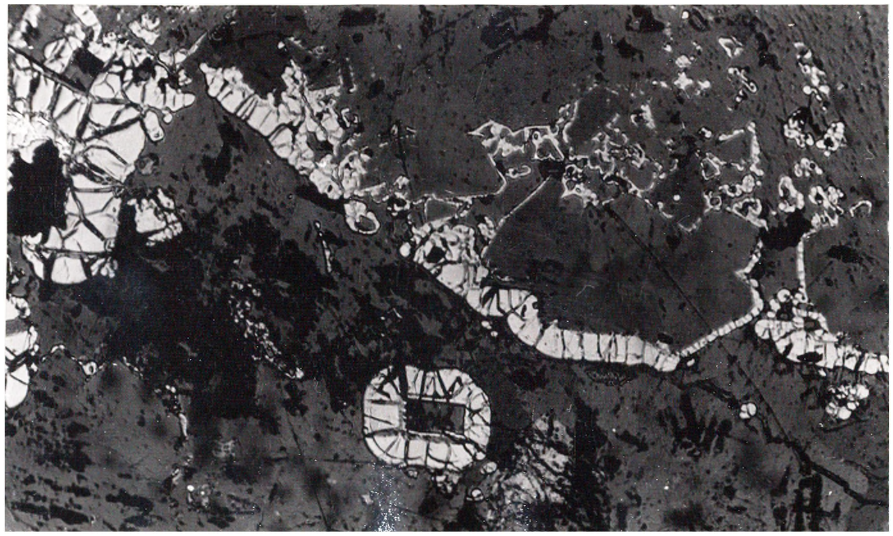


Figure 27c. Sample A-3, Adrianita prospect. Individual ring-like of colloform pitchblende, at upper part a suggestive dendritic form. 150X.

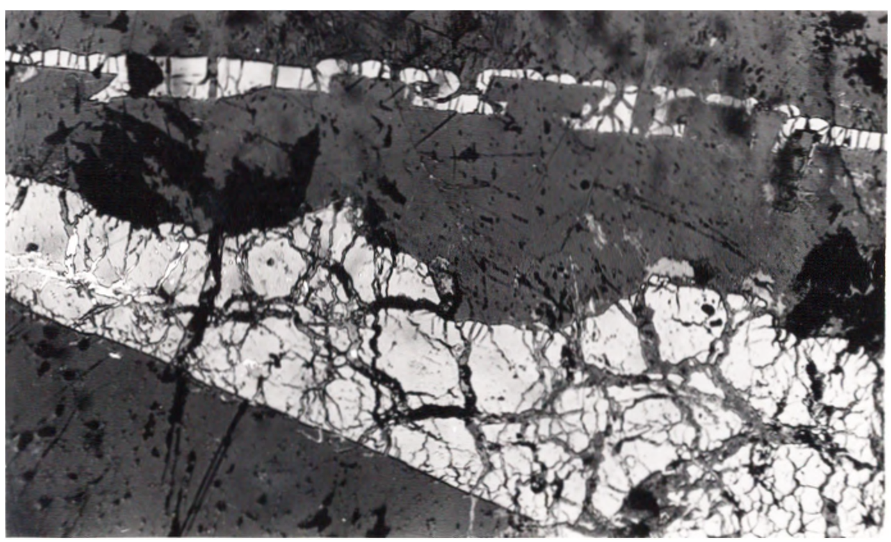


Figure 27d. Sample A-3, Adrianita prospect. Quasi-graphic pitchblende texture, radiogenic ~~above cracks in the~~ lead in the fractures (light). 150X.

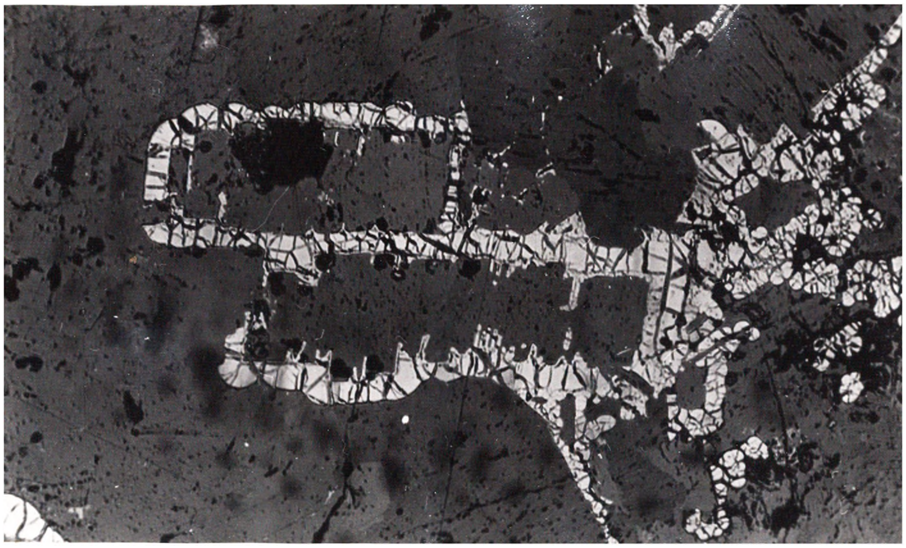


Figure 27e. Sample A-3, Adrianita prospect. Polygonal pattern of pitchblende in carbonate gangue. 150X.

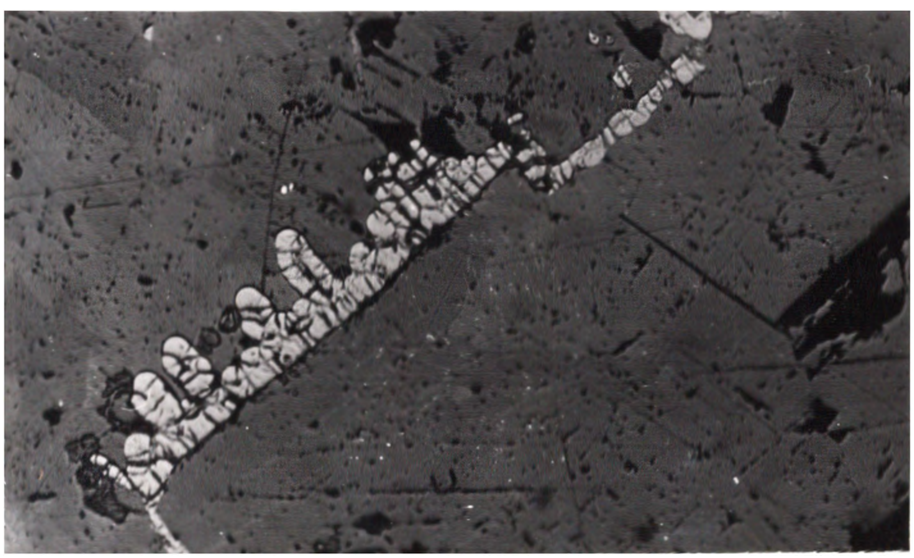
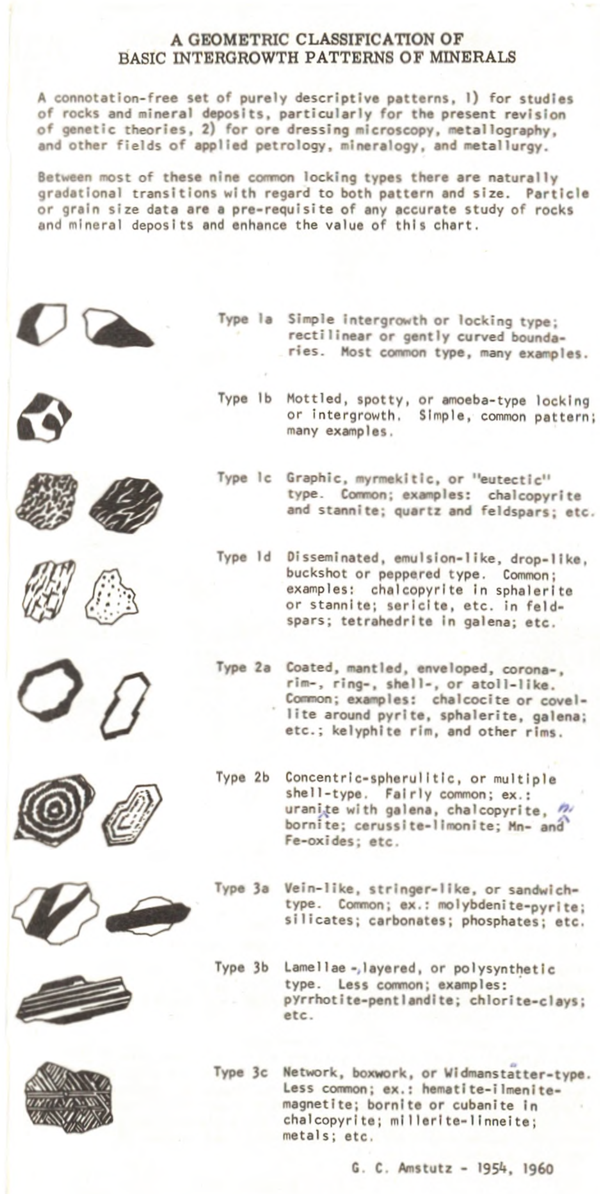


Figure 27f. Sample A-3, Adrianita prospect. The same pattern as above with mushroom shaped extrusions. 150X.

Figure 27g. Sample A-3, Adrianita prospect. Grain boundary seams of pitchblende in carbonate gangue. The lines of the seams are determined by the boundaries of calcite grains. 150X.



A GEOMETRIC CLASSIFICATION OF
BASIC INTERGROWTH PATTERNS OF MINERALS

A connotation-free set of purely descriptive patterns, 1) for studies of rocks and mineral deposits, particularly for the present revision of genetic theories, 2) for ore dressing microscopy, metallography, and other fields of applied petrology, mineralogy, and metallurgy.

Between most of these nine common locking types there are naturally gradational transitions with regard to both pattern and size. Particle or grain size data are a pre-requisite of any accurate study of rocks and mineral deposits and enhance the value of this chart.

Type 1a Simple intergrowth or locking type; rectilinear or gently curved boundaries. Most common type, many examples.

Type 1b Mottled, spotty, or amoeba-type locking or intergrowth. Simple, common pattern; many examples.

Type 1c Graphic, myrmekitic, or "eutectic" type. Common; examples: chalcopyrite and stannite; quartz and feldspars; etc.

Type 1d Disseminated, emulsion-like, drop-like, buckshot or peppered type. Common; examples: chalcopyrite in sphalerite or stannite; sericite, etc. in feldspars; tetrahedrite in galena; etc.

Type 2a Coated, mantled, enveloped, corona-, rim-, ring-, shell-, or atoll-like. Common; examples: chalcocite or covellite around pyrite, sphalerite, galena; etc.; kelyphite rim, and other rims.

Type 2b Concentric-spherulitic, or multiple shell-type. Fairly common; ex.: uranite with galena, chalcopyrite, bornite; cerussite-limonite; Mn- and Fe-oxides; etc.

Type 3a Vein-like, stringer-like, or sandwich-type. Common; ex.: molybdenite-pyrite; silicates; carbonates; phosphates; etc.

Type 3b Lamellae-, layered, or polysynthetic type. Less common; examples: pyrrhotite-pentlandite; chlorite-clays; etc.

Type 3c Network, boxwork, or Widmanstätter-type. Less common; ex.: hematite-ilmenite-magnetite; bornite or cubanite in chalcopyrite; millerite-linneite; metals; etc.

G. C. Amstutz - 1954, 1960

Figure 28. Standard locking chart to which reference is made in the descriptions of ore minerals.

B. CALDERON AREA

1. Calderon Prospect

The area of Calderon is characterized by two main features: skarn type rocks and clear fracture systems. The latter play an important role in the localization of ore deposition. The Calderon fracture, in which scanty mineralization was deposited, strikes N20°E and dips 75° to the west. It can be followed 300 m along the surface (see structural map) and runs across the alteration zone.

a. Host Rock. The skarn in which the ore occurs in a fracture zone is used here with no connotation as to specific process of formation. It means any assemblage of silicate minerals of Ca, Mg, Fe, and Mn. In fact a green rock composed of garnet, epidote, hematite, magnetite and calcite makes up 80% of the rock series in the Calderon area. The zone of major alteration (skarn-formation) is by far strongest near the line of contact with the igneous rocks of Permian age. The origin of this aureola of contact metamorphics seems unquestionable because of the closeness and perfect parallelism to the igneous rock contact. However, the question arises when ore deposition took place.

b. Ore Minerals. Mineralization occurs in spotty patterns. Lenses of ore minerals are so erratic within the fractures that they are practically unpredictable. This mineralization is of course caused by contact metasomatism.

The main ore minerals in order of importance are: tetrahedrite, pitchblende, chalcopyrite, and some uncommon sulfoarsenides of Ni-Co. Most remarkable, perhaps, is the intergrowth of pitchblende with massive tetrahedrite, and, on a smaller scale, with niccolite. This is contrary to what was commonly believed, namely that pitchblende is mostly intergrown with niccolite. Indirectly this tetrahedrite-pitchblende relationship may be used in the future as an ore guide in prospecting for uranium minerals in this area. As a result of this microscopic study, it is suggested that the uranium minerals show a strong tendency to be intergrown with and occur with tetrahedrite and niccolite rather than with copper sulfides (chalcopyrite, bornite).

c. Ore Microscopy

Sample number: C-6 (Calderon upper part)

Tetrahedrite
Chalcopyrite
Pitchblende
Cobaltite
Safflorite
Loellingite
Galena
Native Silver

Sample number: C-7 (Calderon lower part)

Pitchblende
Chalcopyrite
Pyrite
Safflorite
Hematite
Apatite (gangue)

For detailed ore microscopy description refer to the descriptive pages which follow.

Sample number: C-6

Locality: Calderon Alto

Megascopic description: Grayish ore, tetrahedrite being the most common copper mineral; small dotts of chalcopyrite scattered all through the samples.

Microscopic description:

Tetrahedrite (70%): In large patches, containing dissemination or veinlets; often parallel to pitchblende, the latter forming a zone between gangue and tetrahedrite.

Chalcopyrite (19%): Although not abundant it is widely scattered and often intimately intergrown in tetrahedrite, in which it usually occupies the central part of the tetrahedrite patches.

Cobaltite (1%): Occurs as idiomorphic crystals in the gangue, but also in the tetrahedrite mass; size of grains about 75 microhs. (see Figure 29d)

Pitchblende (7%): Botryoidal form, ranging in size from 75 to 150 microns; occurs usually bordering carbonate gangue and surrounding groups of sulfides; occasionally intimately intergrown with safflorite-loellingsite. (see Figure 29b)

Safflorite and Loellingite (3%): Occurs as idiomorphic grains in the gangue and occasionally in tetrahedrite, but also intergrown in a mottled fashion with pitchblende (see Figure 29c).

Galena (1%): Almost always in zoned intergrowth with tetrahedrite and sometimes traces of sphalerite surrounding it.

Native Silver: In many places tetrahedrite contains abundant native silver in the form of triangular or wire-shaped dendrites (see Figure 29a and b).

Gangue: Carbonates in grains of 150 average microns size.

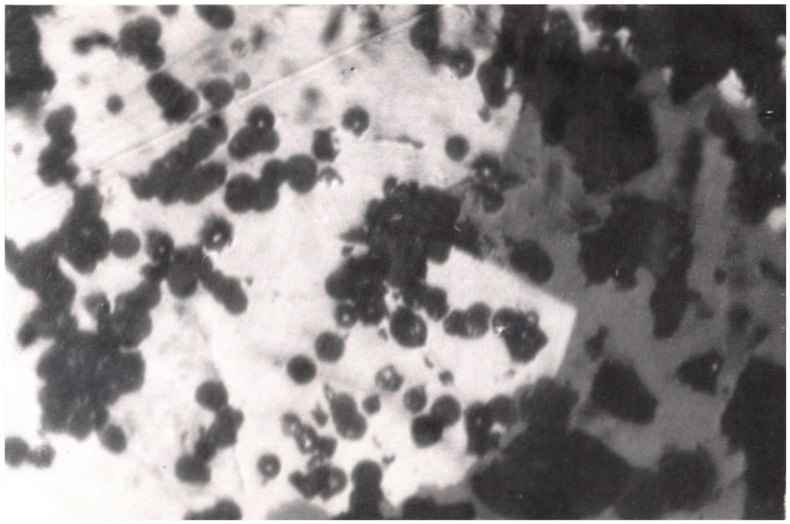


Figure 29a. Sample C-6, Calderon prospect. Spherulites of pitchblende intergrown with chalcopyrite (light color) tetrahedrite to the left side (dark gray) and calcite grains (black) oil. 500X, oil immersion.

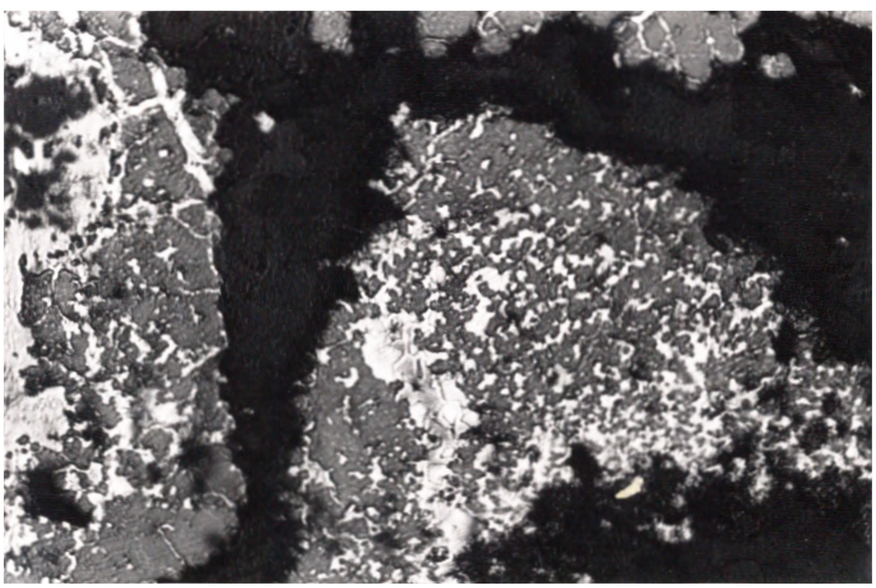


Figure 29b. Sample C-6, Calderon prospect. Pitchblende intergrown in type 1c locking with safflorite - loellingite (central part) to the left is tetrahedrite; black bands are gangue. 500x, oil immersion.

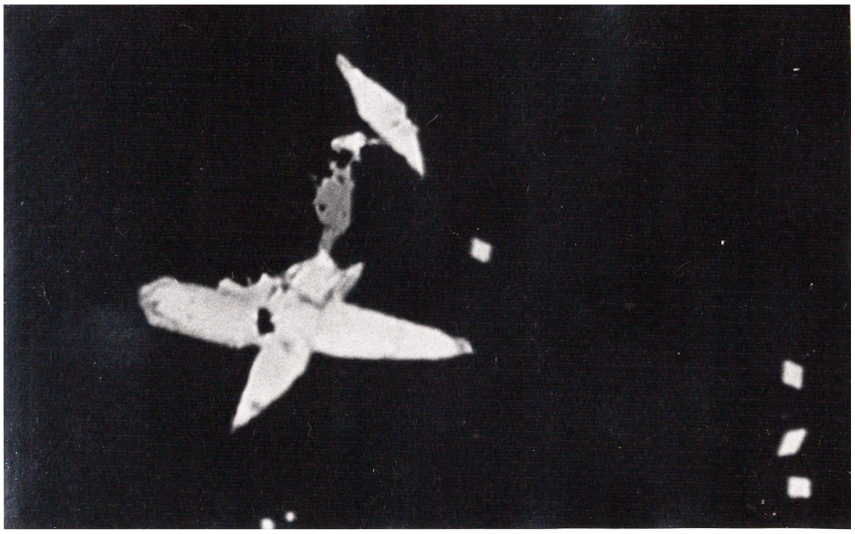


Figure 29c. Sample C-6, Calderon prospect. Idiomorphic grains of safflorite, sometimes interpenetrating, forming rosette-like patterns. Size of the individual grains about 85 microns. 500X, oil immersion.

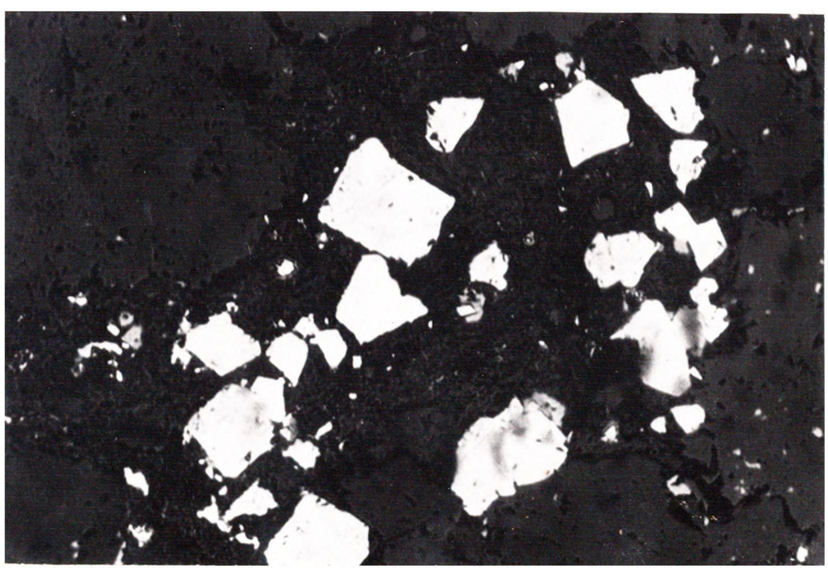


Figure 29d. Sample C-6, Calderon prospect. Cobaltite (white) disseminated in gangue. Average size about 75 microns. 500X, oil immersion.

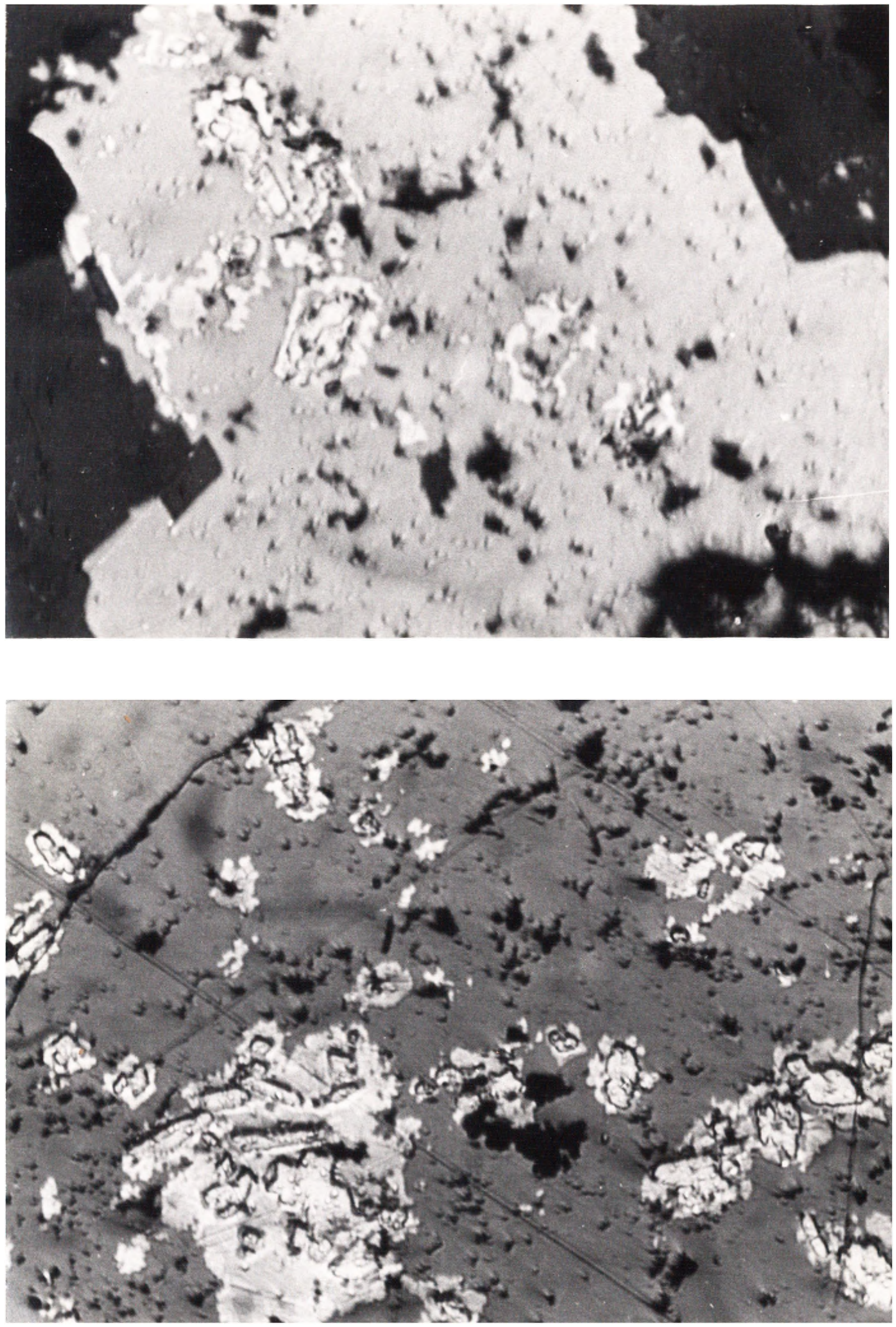


Figure 29e and f. Sample C-6, Calderon prospect. Tetrahedrite in calcareous gangue with chalcopyrite, galena and numerous skeletal crystals of native silver. 500X, oil immersion.

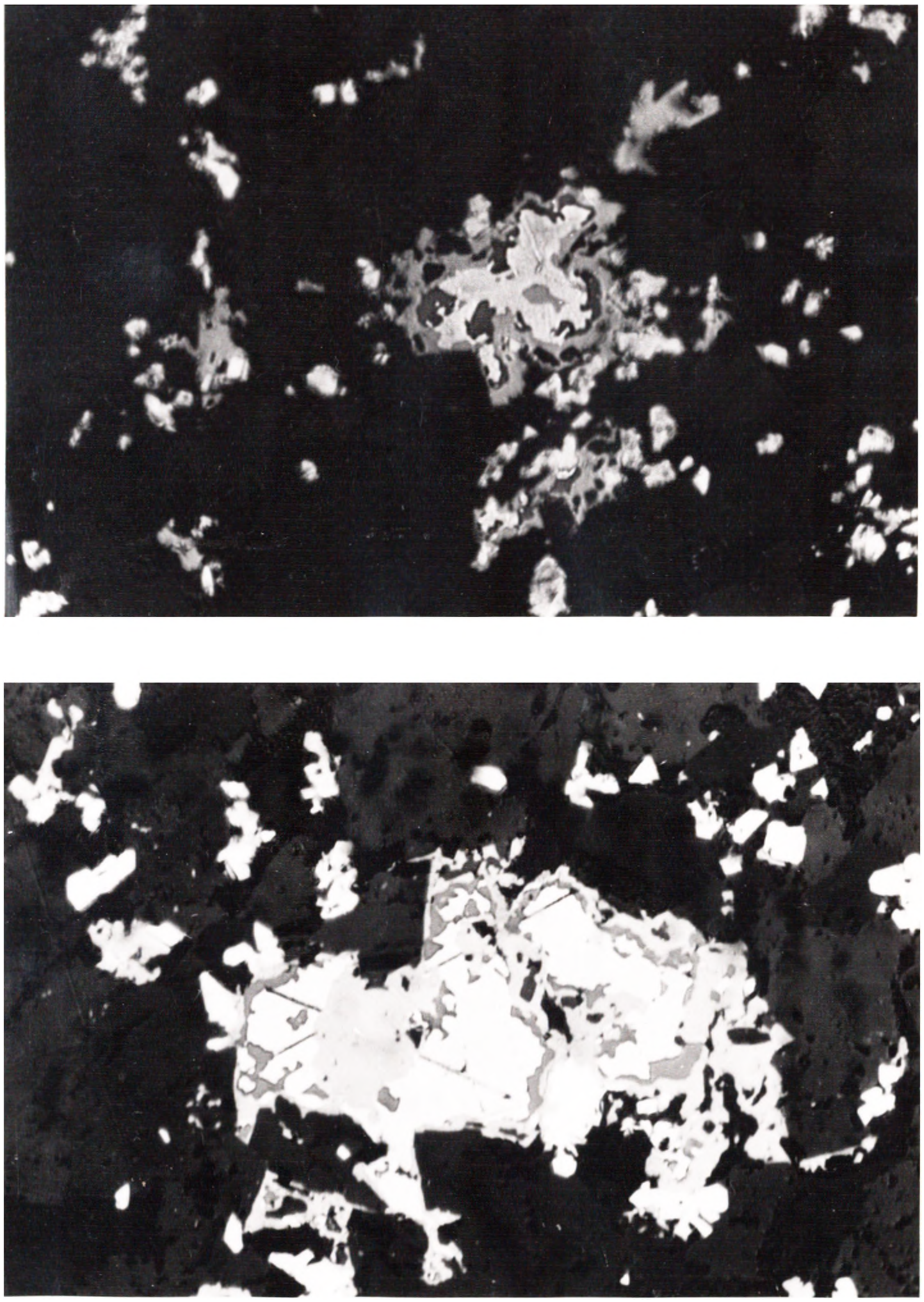


Figure 29g and h. Sample C-6, Calderon prospect. Local zoning patterns of intergrowth between tetrahedrite (light gray) with galena (white) and sphalrite (medium gray). 500X, oil immersion.

Sample number: C-7

Locality: Calderon Bajo

Megascopic description: Pyrite very scattered; distributed in the reddish gangue; iron oxides are widely spread throughout the gangue and give it the red color; hematite also occurs as specularite and in hand specimens it is easily confused with pitchblende; gangue mainly apatite and carbonates.

Microscopic character:

Pitchblende (40%): Massive, botryoidal and dendritic forms; contains very fine grains of chalcopyrite throughout many of the masses; occasionally also euhedral grains of pyrite.

Chalcopyrite (8%): As type lc disseminations in the pitchblende but also as isolated grains elsewhere.

Pyrite (45%): Size of grains ranging from 75 micron to 2 mm. Pitchblende rims the border of the largest grains (Figure 30).

Safflorite and/or Rammelsbergite (traces): Occurs as euhedral grains mostly in the gangue.

Hematite (7%): As isolated islands throughout the sample.

Gangue: Mainly apatite and calcite.

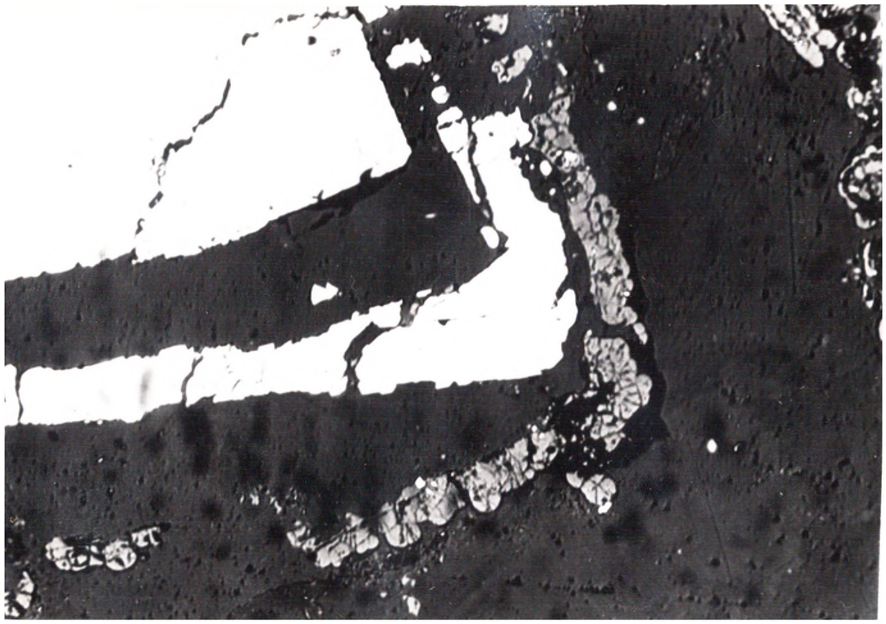


Figure 30. Sample C-7, Calderon Bajo. Pyrite (white), pitchblende (light gray) intergrown in a subparallel pattern in gangue (dark gray). 150X.

2. <u>Aurora Prospect</u>

a. <u>Host Rock.</u> From a lithologic point of view, there is no difference between the Calderon and Aurora areas. Most of the original limestone has been converted to lime-bearing silicates, which is, of course, typical for a contact metasomatic area. The gangue is predominantly dolomitic. The silica content in the gangue increases considerably from the upper to the lower part of the fracture, so that in the lowest portion pyrite mineralization is contained almost always in the silica gangue.

b. <u>Nature of Deposit.</u> The Aurora fracture has been the channelway controlling ore deposition. This fault strikes N 60E and dips NW 80°. The fracture can be followed over a distance of 400 m.

The ore deposition along this fault shows a rough zonal distribution of minerals. The lowest part is represented by a tabular mass of pyrite about 2 m. thick. This pyrite vein outcrops for about 40 m., however, no valuable ore mineral was found in that part.

In the upper part (Aurora Alta) the thickness of main fracture filling and consequently of the main mineralization is restricted to 20 cm. Sporadic niccolite, molybdenite and pitchblende occur along this zone. The mineralization is, however, not entirely confined to veins, but numerous small spots of the same minerals occur in the adjacent country rocks. In general some ore minerals are dispersed anywhere in the altered limestone, as well known from non-contact-metasomatic deposits.

As has already been pointed out, the gangue consist entirely of quartz with minor amounts of carbonate. The middle portion of the fracture is well exposed in a place called "Aurora (Middle part)" from which numerous samples have been studied under the microscope. The minerals here are predominantly pyrite. From the lowest to the middle portion the thickness of the fracture and consequently of the mineralization decreases approximately 1 m. In general, the mineralization in this middle portion shows a brecciated texture, where both siliceous and calcareous gangue and sulfides are broken. Numerous veinlets run parallel to the main fracture in the wall rock. These contain chalcopyrite, bornite, tetrahedrite and small amounts of pitchblende.

c. Ore Microscopy. The study of the polished sections from this area revealed intergrowth of pitchblende with molybdenite. Occasionally the pitchblende is located along the cleavage planes of the molybdenite. Niccolite did not show any intergrowth with pitchblende but rather is intergrown with rammelsbergite in banded or rosette forms. Pitchblende is present in the chalcopyrite as minute spherules.

Sample number: C-1 (Aurora, Upper part)

Niccolite
Molybdenite
Pitchblende
Chalcopyrite
Rammelsbergite

Sample number: C-3 (Aurora, upper part)

Molybdenite
Pitchblende and Uraninite
Chalcopyrite
PYrite
Tetrahedrite

Sample number: C-4 (Aurora, middle part)

Tetrahedrite
Chalcopyrite
Bornite
Covellite
Pitchblende
Pyrite

Sample number: C-5 (Aurora,middle part)

Chalcopyrite
Bornite
Covellite
Tetrahedrite
Pyrite
Chalescite
Pitchblende

Sample number: C-7

Pitchblende
Chalcopyrite
Safflorite-Rammelsbergite
Hematite

Sample number C-5 shows the same features as sample 5', page 155.

Sample number: C-1

Locality: Aurora Alta

Megascopic description: Niccolite, molybdenite and pitchblende distributed between two bands of calcite-dolomite gangue. Oxidation has colored this sample red. Actually it shows a zone predominantly with niccolite and another zone with almost only black ore minerals (pitchblende and molybdenite). This is the only place where pitchblende has the aspects of sooty chalcocite.

Microscopic character:

Niccolite (40%): Occurs as fairly homogenous mass interstitial in calcite-dolomite gangue, often intergrown with a sheet mineral (mica?). The boundaries of niccolite in many cases follow the grain boundaries of the calcite. Niccolite is intergrown with very small amounts of rammelsbergite along the rims. Niccolite is practically never intergrown with molybdenite and pitchblende in this section.

Molybdenite (50%): Shows moderate anisotropism only, and insofar is different from normal molybdenite; deformed basal cleavage is indicated by many sets of parallel sheaves. As shown on Figure 31 of sample C-3, pitchblende appears to follow these directions occasionally but also occurs in random orientation. Perhaps the anomalous pleochroism of molybdenite could be caused by radiation effects. Occasionally tiny grains of chalcopyrite are spread throughout the molybdenite.

Pitchblende (8%): Occurs mostly intergrown with, and occasionally roughly in the same direction as the molybdenite sheaves, but is also found in massive and botryoidal groups. Chalcopyrite appears to be present within some portions of the massive pitchblende as blebs (Figure 31).

Chalcopyrite (3%): Occurs in small amounts as tiny grains in pitchblende or in the gangue.

Rammelsbergite (2%): Along rims of niccolite.

Gangue: Calcite, dolomite, one or two different sheet minerals.

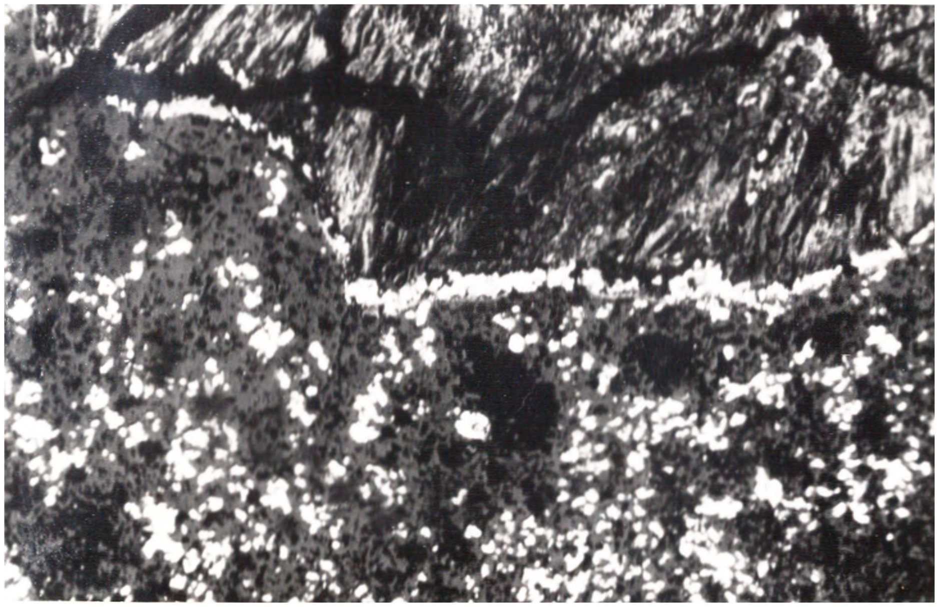


Figure 31. Sample C-1, Aurora Prospect. Chalcopyrite (light) exceptionally intergrown as locking type 1d in the pitchblende; in the upper part flakes of molybdenite are seen. Oil immersion, 500X.

Sample number: C-3

Locality: Aurora alta

Megascopic description: Same as C-2: Molybdenite, pitchblende and calcite in banded arrangement, as vertical veinlets in a calcareous host rock; limonite stain abundant.

Microscopic character:

Molybdenite (80%): Appears to be distributed as scattered patches in the dolomite gangue, oriented as disconnected stringers. Consistently, the sheets are bent (Figure 32a). Although molybdenite is the main ore mineral in total it only amounts to about 3-5% of the whole sample, if the gangue is also counted. Pitchblende appears to be deposited along the lamellae sheets.

Pitchblende and/or uraninite (18%): Occurs in the molybdenite masses, either along its sheets, or cutting them, in fewer cases. It also appears to be bordering the whole molybdenite masses. Pitchblende may have been deposited as uraninite because it shows isomorphic, more or less cubic crystal forms (Figure 32b); but it also occurs as spherulites, which show a tendency to coalesce to form structures suggestive of botryoidal textures (Figure 32a).

Chalcopyrite (2%): Occurs in very small quantity usually as isolated interstitial grains occasionally as patches.

Pyrite, tetrahedrite (tr.): Isolated grains of pyrite and tetrahedrite are found, the latter occasionally rimming chalcopyrite.

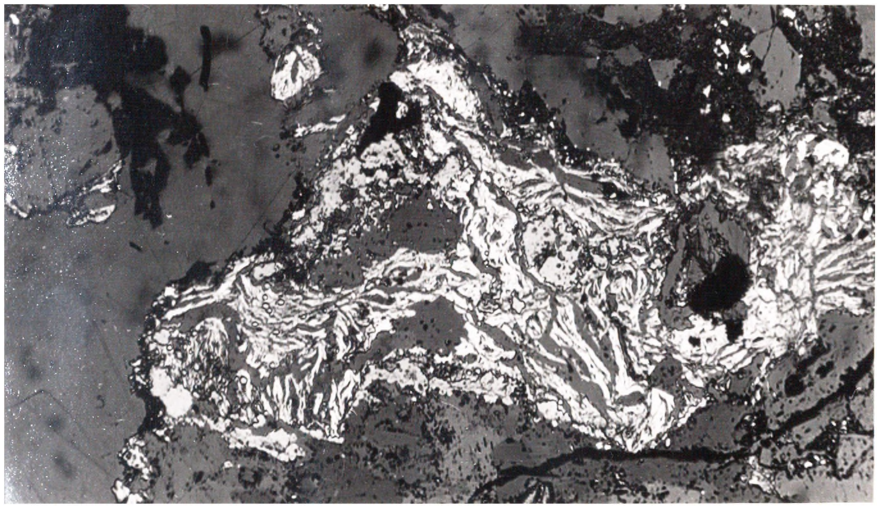


Figure 32a. Sample C-3, Aurora Prospect, upper part. Pitchblende roughly parallel to the borders of molybdenite which are bent and intergrown with a sheety gangue mineral (mica?). 150X.

Figure 32b. Sample C-3, Aurora Prospect, upper part. More or less idiomorphic uraninite. 500X, oil immersion.

Sample number: C-4

Locality: Aurora (lower part)

Megascopic description: Pyrite, chalcopyrite, bornite and covellite are the main minerals. Pyrite shows a banded distribution. Oxidation has entered deeply into the outcrop and therefore the specimens available show much limonite and malachite.

Microscopic character:

Tetrahedrite (37%): The main copper ore mineral occurs in massive textures or intergrown with chalcopyrite, bornite, covellite and pitchblende. Discontinuous grains of pyrite are distributed throughout the tetrahedrite. In some grains of tetrahedrite, chalcopyrite occurs as spots (locking type 1d).

Chalcopyrite (25%): Occurs intergrown with the other copper ore minerals as pointed out above, but also fills cracks in the pyrite, as if it would be a secondary enrichment copper mineral.

Bornite (8%): Scattered intergrowth with chalcopyrite; frequently rimmed and veined by covellite. Bornite also occurs criss-crossing pyrite mass, but this is rather an exception and in this case shows moderate anisotropism.

Covellite (10%): As a rule, covellite is well developed in bornite and occasionally in chalcopyrite.

Pitchblende (5%): Occurs intergrown with tetrahedrite. The lower reflectivity of pitchblende (R = 16%) readily allows differentiation from tetrahedrite (R = 26%). Pitchblende occurs as spotty groups, bands or isolated grains. Veinlets of limonite or chalcopyrite intersect pitchblende.

Pyrite (15%): Cataclastic texture. Occurs as massive or isolated grains up to .5 mm. average grain size. Chalcopyrite and bornite frequently vein isolated grains of pyrite.

Mineral (X): Color grayish to brownish; medium to strongly anistropic, surrounded by tetrahedrite and with about the same reflectivity.

Sample number: C-5'

Locality: Aurora (middle part)

Megascopic description: Chalcopyrite, bornite, covellite and pyrite are the main constituents. They are intergrown in very irregular patterns and show much oxidation.

Microscopic character:

Chalcopyrite (30%): Occurs intergrown with tetrahedrite, bornite, covellite and pyrite. When chalcopyrite occurs with covellite it shows a grid-like texture which is a remnant from the replacement of bornite by covellite. Chalcopyrite does not seem to be changed into covellite at all. Tiny blebs of chalcopyrite appear in the tetrahedrite.

Bornite (18%): Although not abundant it is very widespread. Anisotrop ranges from moderate to very weak; bornite appears to be altered easily to covellite, which is very common in this sample. Bornite shows semigraphic intergrowth with chalcopyrite and usually it veins pyrite.

Covellite (25%): Occurs along rims and grain boundaries of bornite (Figure 33b); also as veinlets in pyrite and chalcopyrite; but on a very small scale.

Tetrahedrite (8%): Occurs in homogenous masses and intergrown with chalcopyrite and covellite.

Pyrite (13%): Cataclastic texture veined and probably partly replaced by chalcopyrite, in a criss-crossing pattern (Figure 33a). Pyrite occurs as stringers or as isolated grains surrounded by chalcopyrite or also as relicts within the carbonates of limonite of the gossan.

Limonite (1%): Gossan product of the sulfides.

Chalcocite (±2%): Intimately intergrown with covellite.

Pitchblende (3%): Usually intergrown with limonite (secondary).

Gangue: Mostly carbonates.

Sample Number 5 shows the same characteristics as sample number 5'.

Figure 33a. Sample C-5', Aurora Prospect, middle part. Fractures in pyrite (light) with chalcopyrite (light gray) and covellite (darker veinlets). Any dark gray is gangue. 150X.

Figure 33b. Sample C-5, Aurora Prospect, middle part. Bornite (light gray) breaking down into covellite (gray); chalcopyrite, hardly affected by this alteration (white). 150 X.

VI. CONCLUSIONS

The field study of the two mineralized zones of Huamanapi and Calderon in the Vilacabamba area resulted in the following conclusions:

The stratigraphic study revealed that the Copacabana group is of Upper Pennsylvanian and Lower Permian age. The Tarma group is of Middle Pennsylvanian age and may be considered as the base of the Copacabana group, while the continental Negrillas conglomerate may be of Mississippian age.

The intrusive and intrusive rocks of the area are of Permian and of Tertiary age. They include acidic, intermediate and basic rocks, as described.

The study of the mineralization lead to the following concept of ore deposition: In the Huamanapi zone ore minerals occur as veinlets or as small wide spread lenses. Pitchblende in the Copacabana group may occur any place throughout the whole thickness, as patches, veinlets or lenses of erratic distribution. In the Calderon zone minerals occur as fissure fillings in a skarn zone.

The gradational distribution of the ore minerals and of the skarn alteration products indicate a genesis by contact metamorphism, with variable degrees of migration of the hydrothermal ore solutions and intensity of metasomatism.

At least two possibilities exist in regard to the possible source of the ore solutions:

1. The Permian Mitu igneous rocks, which crop out along the skarn zone along the Calderon fault, may have furnished the solutions which formed the ore deposits.

2. The Tertiary granites of the Vilcabamba-Machupichu-batholith may extend below this zone and may have furnished mineralizing solutions. This batholith crops out only 5 km. southwest of the area at a location called Huashuacocha Lake. Here, as in various other portions of the batholith, veinlets or disseminations of pitchblende are present. Also, a uranium-copper-nickel-cobalt sulfide prospect almost identical with those at Huamanapi is known in Punta Rayoc only 700 m. away from an outcrop of granite.

There may be other possibilities for source of ore solutions, although to date no direct indications have been found. The igneous rock samples M-1, M-2, M-3 for example, which form dikes and plugs, do not seem to be connected in any way with the mineralizations.

The microscopic study indicates that the principal ore minerals in order of importance are: copper sulfo arsenides, copper sulfides, pitchblende and niccolite. Molybdenum and Cobalt minerals are very minor constituents.

The relations of Cu-Ni sulfoarsenides or arsenides and pitchblende are "symphatetic" or synbatic, e.i., they show affinity for uranium.

Most of the pitchblende occurs intergrown with tetrahedrite. This observation may be used for practical purposes during the prospection for uranium in the Vilcabamba area.

The relationship between pitchblende and pyrite are "anti-pathetic", i.e., in the course of the study of the polished sections, pitchblende has not shown to be ingrown with pyrite. The relationship between bornite, chalcopyrite and uranium is obscure. Occasionally spherulites of pitchblende are found in chalcopyrite. From the skarn alteration and the vein-like cross-cutting nature of large portions of the deposit, it seems that the solutions were derived from an igneous source.

Pitchblende may be expected to be found in any fissure veins containing tetrahedrite and niccolite, but in subordinate amounts. The occurrence of pitchblende as a colloform mineral rather than as isometric uraninite may perhaps be considered evidence for deposition at low temperature and pressure. On the other hand, the presence of a skarn-type zone, containing abundant magnetite, specular hematite, garnet epidote and other Fe-Mg-Silicates may be indicative of reasonably elevated temperature. The presence of abundant apatite near the borderline of the limestone to igneous rocks is also a skarn feature.

The skarn zone is directly related to the contact limestone-volcanics, which is older than the deposition of the ore minerals as mentioned above.

In conclusion, the deposits described in this thesis may be classified in Group 12 and 29 of RAMDOHR's system reproduced on Table V, since the source and nature of the solution appears to be hydrothermal, and since the place and process of deposition was connected with an igneous contact.

TABLE V. ISOGENETIC CLASSIFICATION OF ORE DEPOSITS

(Classification of ore minerals according to their parageneses)
(After RANDOHR, 1960, with minor modifications)

			32	Katazone	
Metamorphic Sequence		Metamorphosis	31	Mesozone	
		under stress	30	Epizone	30
			29	Contact-metamorphosis	
		ore deposition	28	Mineral fuels (caustobiolites)	
		through	27	sedimentary sulfide deposits	
		precipitation	26	Concentration in arid basins	
Sedimentary Sequence			25	Descendent dykes and replacements	25
		ore deposition through	24	Cementation-zone (often enriched)	
		weathering	23	Oxydation-zone	
		volcanic-	22	Placer deposits	
		(extrusive)	21	Mixed deposits (partic."sterile hot Spr's")	
			20	Volcanic-exhalative deposits	20
		magmatic	19	Volcanic-intramagmatic	
		subvolc.	18	Hg - Sb - Formation	
		hydro-	17	Cu - Pb - Zn Formation	
		thermal	16	Au - Ag - Formation	
Magmatic sequence			15	Sulfide - lean - formation	15
	Intrusive Magmatic		14	Cu - siderite - formation	
		hydro-	13	Ag - Sn - Zn - Formation	
		thermal	12	Ag - Co - Ni - U - Bi - As - For.	
			11	Low temperature Zn - Pb - For.	
		stage	10	Pb - Zn - Ag - Formation	10
			9	Cu - As - Fe - Formation	
			8	Au Fe - Formation	
		pegmatit.	7	Pneumatolytic impregnations	
		pneumato-	6	Contact - pneumatolytic deposits	
		lytic	5	Pneumatolytic deposits	5
		stage	4	Pegmatites	
		intra-	3	Intrusive ore - injections	
		magmatic	2	Liquidmagmatic unmixing	
		stage	1	Crystallization differentiates	

VII. B I B L I O G R A P H Y

ADAMS, G. I. (1908) An outline review of the geology of Peru, Ann. Rep. Smithson. Inst. 1908, p. 385-430.

AGUILAR, O. V. Jordan, A. Ocampo and J. Pizarro (1957) Estudio geologico y de radioactividad, distrito de Vilcabamba, departmento del Cuzco, Peru. Junta de Control Energia Atomica, Peru, unpublished internal report.

__________, J. Sosa and E. Goyburn (1959) Reconocmiento geologico - radiometrico de la Zona quebrada de Negrillas, distrito de Vilcabamba, provincia de la Convencion, departmento del Cuzco. Junta Control Energia Atomica, Peru. (unpublished internal report)

AHIFELD, R. (1960) Geologia de Bolivia, Editorial Don Bosco, Instituto Boliviano de Petroleo, 245 p.

AMSTUTZ, G. C. (1959) The genetic meaning of the terms hydrothermal and replacement. (Ann. Meeting, Institute of Lake Superior Geology, Minneapolis, 12-14 April).

__________. (1960) The copper deposits Caprichosa and Antachajra in Central Peru (with notes on ore genesis in general) N. Jb. Miner. Ahb., 94, p. 390-429.

__________. (1961) Origen de los depositez minerals congru-entes en formaciones sedimentaries. II Cengreso Nac. Geol. Peru (Dic., 1960) Bol. Soc. Geol. Peru 36, 18 p.

BADGLEY, P. C. (1959) Structural methods for the exploration geologist. Harper, New York, 280 p.

BALTA, G. (1899) El Sistema carbonifero en el Peru. Rev. Cienc. Bol. min. Ind. Condtr. 15, p. 68-72, 82-86.

BINGHAM, H. (1912) The Discovery of Pre-Historic Human remains near Cusco, Peru. Am. Jour. Sci. 33, p. 297-305.

BISBY, H. E. Franklin, and D. Tylor (1956) Instrumental developments in the prospecting, mining and chemical processing of nuclear materials. In: Peaceful uses of atomic energy. Proc. Int. Conf. Peaceful uses of Atomic Energy, V. 6, Geology of uranium and thorium, United Nations, Geneva, p. 704-711.

BOWMAN, I. (1916) The Andes of Southern Peru Am. Geog. Soc., Special Publication, 336 p.

BURRI, C. and P. NIGGLI (1945) Jie jungen Eruptirgesteine des mediterrean Orogens. Publ. "Vulkaninstit. Immanuel Friedtander" no. 3, 654 p.

DAVIDSON, C. F. and H. U. Bowie (1956) Methods of prospecting for uranium and thorium. In: Peaceful uses of atomic energy. Proc. Int. Conf. Peaceful uses of Atomic Energy F.M. 6, Geology of uranium and thorium, United Nations, Geneva, p. 659-662.

DAVIS, F. J. (1954) Seintillation counters. In: Nuclear Geology (edited by H. Fault). Wiley, New York: p. 31-35.

DERRIKS, J. J. and J. F. Vaes (1956) The Shinkolobive uranium deposit: Current status of our Geological and Metallogenic Knowledge. Proceeding of the Peaceful Uses of Atomic Energy. V. 6, Geology of Uranium and Thorium, p. 94-128.

D'ORGIGNY, A. (1842) Voyages dan I'Amerique meridionale de 1826-1833. t. 3, pt. 4, peleontogie, 188 p.

DOUGLAS, J. A. (1914) Geolgical section through the Andes ~~of~~ Peru and Bolivia: 1. - from the coast of Africa in the north of Chile to La Paz and the Bolivian "Yungas". Quart. Jour. Geol. Soc. 70, p. 1-53.

__________. (1920) Geological section through the Andes of Peru and Bolivia: II. From the Port of Hollendo to the Inanbary River. Quart. Jour. Geol. Soc. 76, p. 1-59.

__________. (1921) Geolgical Section through the Andes of Peru and Bolivia. III. From the Port of Callao to the river Perene. Quart. Jour. Geol. Sec. 77, p. 246-284.

__________. (1932) The geology of Marcapat Valley in eastern Peru, with an Appendix on the Graptolite from the Quitare area by Oliver Meredith. Quart. Jour. Geol. Soc. 89, part 3, p. 308-356.

DUEÑAS, E. (1925) Raszos fisiograticos fundamentales del territoric peruano. Soc. Geol. Peru, t. 1, p. 31-60.

DUNBAR, O. and N. Newell (1946) Marine Early Permian of the Central Andes and its fusuline taunas. Am. Jour. Sci. 244, p. 377-402, 457-491.

EASTON, F. (1914) Vertebrate Fossils from Ayusbamba, Peru. A. Jour. Sci., fourth series, 37, p. 141-154.

EDWARDS, A. B. (1954) Textures of the Ore Minerals and their Significance. Hustralasian Inst. Mining and Metal. 242 p.

EGELER, C. G. and De Booy (1956) Geology and Petrology of Part of the Southern Cordellera Blanca, Peru. Verh. Kon. Ned. Geol. Mijnb. Gen., Geol. Ser., pt. 17.

EVERHART, D. L. and R. J. Wright (1953) The Geological Character of Typical Pitchblende Veino. Econ. Geol. V. 48, p. 77-94.

FORBES, D. (1861) Report of the Geology of South America Pt. I. Bolivia and Southern Peru; with notes on the fossils by Huxley, Salter, and Jones. Quart. Jour. Geol. Soc. London. 17, p. 7-62.

FRICKER, P. (1960) Die geologische Arbeit Wahrend der Eruptivegenteine in der Cordillera Vilcabamba (Peru). Schweiz, Min. Petr. Mitt., Band 40, Heft 2, p. 359-282.

FRONDEL, C. (1958) Systematic mineralogy of Uranium and thorium. U.S. Geol. Surv. Bull. 1064, VIII. + 400 p.

GABB, W. W. (1877) Description of a Collection of Fossils, Made by Doctor Antinio Raimondi in Peru. Jour. Acad. Nat. Sci. Phila. Ser. 2 V. VIII (1874-81) p. 263-336.

GABELMAN, J. W. (1958) Second visit to Vilcabamba area, Department of Cuzco, Peru. Junta de Control de Energia Atomica, Peru, unpublished internal report, no. 38, 4 p.

GANSSER, A. (1950) Geological and Petrographical notes on Gorgona Island in relation to northwestern S. America. Schweiz. Min. Petr. Mett. Band 30, Heft 2, p. 219-237.

GEFFROY, J. (1960) Study of some polished sections from Huamanapi and Calderon Zones. Centro de Estudios Nucleares de Fontenay-aux-Roses. Comisariato de Energia Atomica, France, unpublished internal report no. 1382, 6 April V 60, 9 p.

GEORGE, D. (1949) Mineralogy of Uranium and Thorium U.S. Atomic Energy Commission. RMO-563,198 p.

GREGORY, H. E. (1912) The rodadero (Cuzco-Peru), a fault plane of unusual aspect. Am. Jour. Sci. fourth Series 27, p. 289-298

__________. (1913a) Geological sketch of Titicaca Island and adjoining areas. Am. Jour. Sci., fourth series, 36, p. 187-212.

__________. (1913b) Gravels at Cuzco, Peru. Am. Jour. Sci., Fourth Series, 36, p. 15-29.

__________. (1914) Geological reconnaissance of the Ayusbamba (Peru) fossil beds. Am. Jour. Sci., fourth series, 37, p. 125-154.

__________. (1916) A geologic reconnaissance of the Cuzco Valley, Peru. Am. Jour. Sci. 41, p. 1-100.

HARRISON, J. V. (1943) The geology of the Central Andes in part of the province of Junin, Peru. Quart. Jour. Geol. Soc. London 99, p. 1-36.

HEINRICH, Wm. (1958) Mineralogy and geology of radioactive raw materials. New York, McGraw Hill, 654 p.

JENKS, W. F. (1946b) Preliminary note on geological studies of the Pacific slope in Southern Peru. Am. Jour. Sci., 244, p. 367-372.

KATZ, H. R. (1959) Zur Geologic des Palaoroikums in den surdostlichen Andes von Peru. Eclogae Geol. Helvet. 52, Nr. 2, p. 721-734.

KERR, P. (1956) Rock alteration criteria in the search for uranium. Peaceful uses of Atomic Energy. V. 6, Geology of Uranium and Thorium, p. 679-84.

______. (1959) Optical mineralogy. McGraw Hill, New York. 442 p.

KIDD, F. and H. H. Haycock (1935) Mineragraphy of the ores of Great Bear Lake. Geol. Soc. Am. Bull, v. 46, p. 879-960.

KOZLOWSK, R. (1923) Faune Devonienne de Bolivia, Ann. de Paleont., t. 12, 112 p.

LEBEDEV, V. I. (1961) On the causes of the oxidation of Uranium in Uraninites. International Geology Review. v. 3, N° 1, p. 1-4.

LISSON, C. I. (1925) Como se genero el suelo perua. no. Soc. Geol. Peru, t.d., p. 92-126.

McKINSTRY, H. E. (1955) Structure of Hydrothermal Ore Deposits. Ecm. Geol. 50th Ann. Volumn pt. I, p. 170-218.

MALDONADO, E. (1918) Contribucion al estudio de la geologia de Sicuani, Revista Universitaria, Ano 13, t. 2, Lima, p. 480-494.

NEWELL, N. D. (1946) Geological investigation around Lake Titicaca. Am. Jour. Sci. V. 244, p. 357-366.

________. (1949) Geology of the Lake Titicaca Region, Peru and Bolivia. Geol. Soc. Am. Mem. 36, 111 p.

________, J. Chronic and T. C. Roberts (1953) Upper Paleoroic of Peru. Geol. Soc. Am. Memo 58, 276 p.

NININGER, R. D. (1956) Minerals for Atomic Energy D. Van Nostrand, Princeton, New Jersey, 381 p.

PEIRSON, D. H. and E. Franklin (1951) Aerial Prospecting for radioactive minerals. Journ. Appl. Phys. 2, p. 281-291.

PETERSEN, U. (1958a) Structure and uplift of the Andes of Peru, Bolivia, Chile and adjacent Argentina. Bol. Soc. Geol. Peru, 33, p. 145-218.

PETERSEN, U. (1958b) Plutones y Mineraliracion en los Andes del Peru, Bolivia y Chile. Bol. Soc. Geol. Peru, 33, p. 219-239.

RAIMONDI, A. (1902) El Tomo IV del Peru. Inf. Mem. Bol. Soc. Ings., Lima, Peru, v. IV, N° 3-4 y 5, p. 101-106.

RAMDOHR, P. (1960) Die Errmineralien Und ihre Verwachsungen. Akademie-Verlag, Berlin, 1089 p.

ROGERS, K. J. and B. V. Coronado (1954) Radioactivity in the Vilcabamba mining district, province of La Convencion, department of Cuzco, southern Peru. Junta de Control Energia Atomica, Peru, unpublished internal report, 22 p.

SOSA, J. and E. GOYBURY (1959) Reconocimiento geologico - radiometrico del area de Minaspata, distrito de Vilcabamba, provincia La Convencion, departamento del Cuzco, Peru. Junta Control Energia Atomica, unpublished internal report, no. 45, 11 p.

STEAD, F. W. (1956) Instruments and Techniques for Measuring radioactivity in the field. In: Peaceful uses of Atomic Energy. Proc. Int. Conf. Peaceful uses of Atomic Energy, vol. 6, Geology of uranium and thorium, United Nations, Geneva, p. 714-721.

STEINMANN, G. (1930) Geologia del Peru. Winters, Heidelberg, 448 p.

TURNER, F and J. Verhoogen (1951) Igneous and Metamorphic Petrology. McGraw-Hill, New York, 602 p.

WAHLSTROM, E. E. (1960) Optical Crystallography John Wiley, New York, 356 p.

WATANABE, T. (1960) Characteristic features of ore deposits found in contact-metamorphic aureoles in Japan. International Geol. Review, v. 2, N. 11, p. 946-966.

WEEKS, L. G. (1948) Paleogeography of South America. Geol. Soc. Am. Bull., vo. 59, p. 249-282.

WILLIAMS, H. F. J. Turner and Ch. M. Gilbert (1954) Petrography, an introduction to the study of rocks in thin sections. W. H. Freeman, San Francisco, 406 p.

WILSON, E. E., V. C. Rhoden, W. W. Vaughn, and H. Faul (1954) Portable Scentillation counters for geologic use, U. S. Geol. Surv. Cir. 353.

WINCHELL, A. N. (1951) Elements of Optical Mineralogy, an introduction to microscopic petrography. John Willey, New York, 551 p.

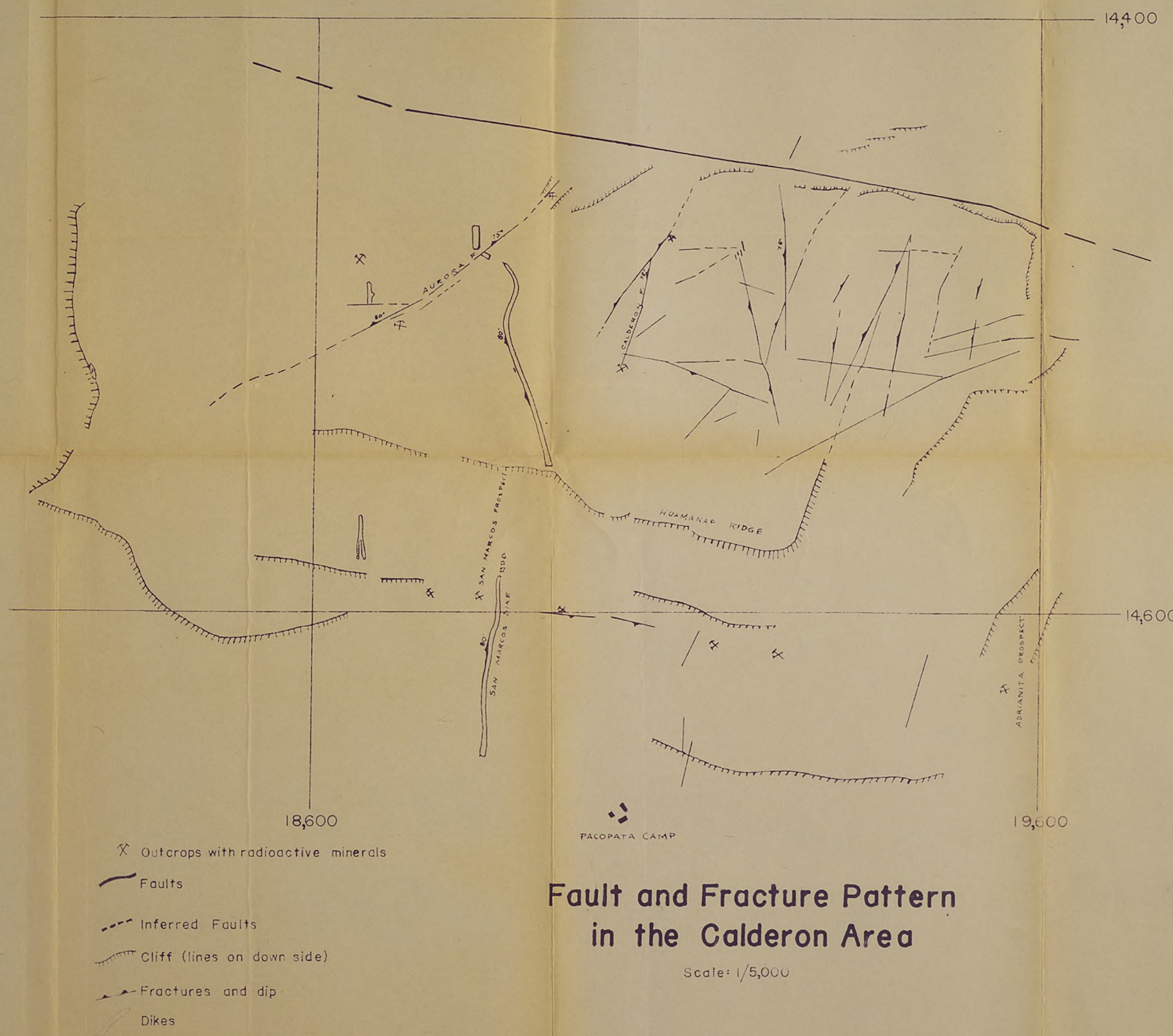
VITA

Oscar Aguilar was born in Conchucos, Peru on 10 January 1930. He attended the "Primaria" (elementary school) from 1936 to 1941, and "Secundaria" (high school) from 1942 to 1946.

In 1948 he enrolled in the Department of Geology of the Universidad Major de San Marcos and in December, 1953, he received the degree "Ingeniero Geologo". Following graduation he worked as an assistant geologist with Cerro de Pasco Corporation, working in different mines of the Peruvian Andes until 1955. From 1955 until August 1960 he was a member of the geological staff of the Atomic Energy Commission of Peru and worked in the radioactive minerals prospecting division in southern and northern Peru.

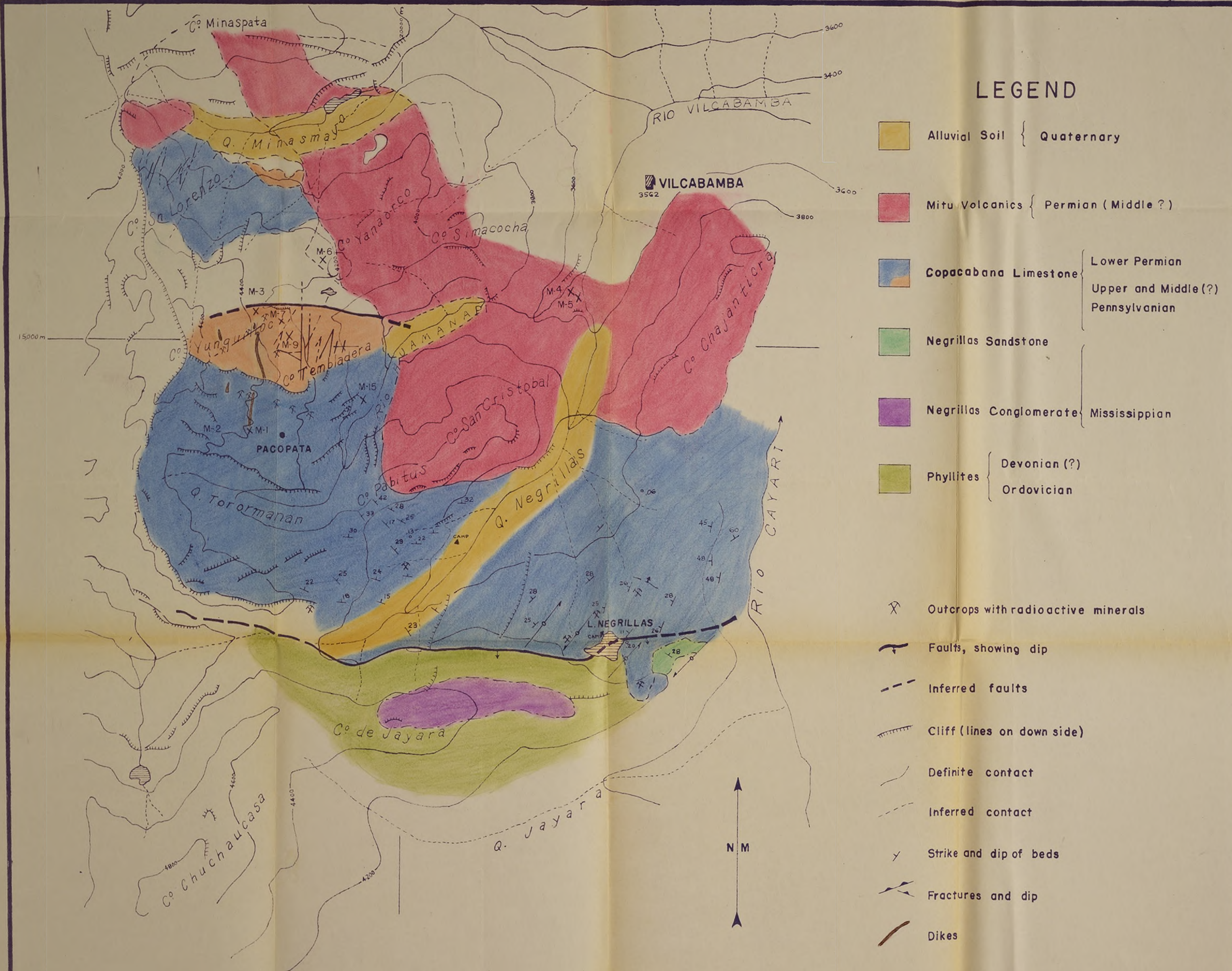
He came to the United States and enrolled in the graduate school of the University of Missouri, School of Mines and Metallurgy, in September 1960.

He is a member of the following professional societies: American Institute of Mining, Metallurgical and Petroleum Engineers; Geochemical Society; Sigma Gamma Epsilon; Photogeological Society; International Association of Sedimentalogy; Sociedad Geologica del Peru; Association Nacional de Geologos del Peru. He is an associate member of Sigma Xi.



Fault and Fracture Pattern in the Calderon Area

Scale: 1/5,000



Geologic Reconnaissance Map of the Thesis Area
(Including the Huamanapi, Calderon and Negrillas Zones)
District of Vilcabamba, Province of La Convencion, Dept. of Cuzco, South Peru
Scale: 1/20,000 April, 1962